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SOLAR AND STELLAR CORONAL PLASMAS

Grant NAGW-112

Semiannual Progress Report No. 9

For the period 1 November 1984 through 30 April 1985

Principal Investigator

Dr. Leon Golub

April 1985

Prepared for

National Aeronautics and Space Administration

Washington, DC 20546

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PROGRESS REPORT

I. Publications

The following papers have been completed during the past six months and represent the progress made in describing and interpreting coronal plasma processes and the relationship between the Solar corona and its stellar counterparts:

"On Stellar X-ray Emission", by R. Rosner, L. Golub and G.S. Vaiana, is a review article which will appear in Annual Reviews of Astronomy and Astrophysics. This article describes the manner in which Solar Physics, Stellar Physics and General Astrophysics have joined together into the entirely new discipline of stellar x-ray astronomy. A central issue throughout the review is the extent to which extrapolations from solar physics are justifiable and the manner in which stellar observations are being used to augment and test the solar studies. Topics discussed include: "X-ray Emission From Stars", "The Solar Analogy and Modelling of X-ray Emission", "The Physics of X-Ray Emission from Solar-Type Stars", and "The More General Astrophysical Context". The paper concludes by outlining the most pressing problems in coronal physics and discussing prospects for their solution.

The paper "EINSTEIN X-ray Survey of the Pleiades", by G. Micela et al. has been accepted for publication in the Ap. J. This paper represents a significant step in understanding the relationship between the interior structure of solar-type stars, the presence of dynamo activity and the type and strength of coronal activity which results. Prior

to these observations, a clear correlation had been observed between the strength of x-ray emission from solar-type stars and the rotation rates of the stars. The link has been presumed to be via strong internal differential rotation which causes vigorous magnetic field production and results in the observed x-ray activity. Young stars in general rotate rapidly and have high levels of x-ray emission; the only exception has been stars earlier than A7, which do not have significant outer convection zones and are not detected in x-rays.

The Pleiades observations show an apparent contradiction with this picture, because although the G-stars in the cluster are strong x-ray emitters, the K-stars are relatively weak in spite of their very rapid rotation rates; moreover, few if any M-dwarfs are detected even though most nearby M-dwarfs are strong and highly variable x-ray sources. The key to the puzzle appears to be the fact that the Pleiades is a very young cluster and that the K and M stars may not yet be evolved onto the main sequence. The G-dwarfs are just old enough to have settled into a structure with an outer convection zone and a rapidly rotating core. This interpretation strengthens the case for those solar dynamo models which involve magnetic field amplification at the base of the HCZ, at the shear interface with a radiative core.

The paper "Closed Coronal Structures VI...", described in our last progress report was revised and has appeared in the Ap.J. In addition, the paper, "X-ray Survey of Main-Sequence Stars With Shallow Convection Zones" has appeared in the Ap.J. and discusses the onset of convection in solar-type stars and its relation to the dynamo and magnetic field-related activity.

The paper "Implications of the 1400 MHz Flare Emission..." by Holman, Bookbinder and Golub, was presented at the conference on Stellar Con- Tinuum Radio Astronomy in Boulder, CO. The paper compares solar and stellar radio flares and discusses the possible emission mechanisms by which the high brightness temperature of > 10^{13} K could be produced by solar-type flares. Predictions of emission properties such as polarization, variability timescales and source size can be coupled with measurements of x-ray emission and magnetic field strength in order to test Solar flare models in a more extreme parameter regime.

A paper in progress, "On Magnetic Field Stochasticity..." by Antonucci, Rosner and Tsinganos uses SMM data on line broadening during Solar flares in order to test a radical new theory of Solar flare triggering and development. Results indicate that flares may be caused by a process which leaves the external appearance of loops nearby unchanged (initially) but produces completely disordered field line structures within the loop. Microscopic turbulence and globally incoherent heating would then be properties of the initial flare onset. This view seems to explain many of the previously puzzling features of the BCS and SXP data.

II. Talks, Abstracts and Invited Presentations

"An X-ray Survey of Solar-Type Stars" by J. Bookbinder, P. Majer, L. Golub and R. Rosner, 165th AAS Meeting, Tucson.

"Correlation Between X-ray Luminosity and Rossby Number", by G. Micela, S. Sciortino and S. Serio, Symposium "X-ray Astronomy in 1984", Bologna, Italy.

"Optimized Variability Analysis in Non-Periodic Sources", by A. Collura, S. Sciortino, A. Maggio, S. Serio and R. Rosner, Bologna Symposium.

"X-ray Variability in K and M Dwarfs", by C. Ambruster, S. Sciortino and L. Golub, abstract to 166th AAS Meeting.

"The Time Resolution Domain of Stellar Radio Astronomy", by J. Bookbinder, paper to appear.

"Theory Tested by Means of the Stars", by L. Golub, NASA CP-2358, eds. Underhill and Michalitsianos.

"Implications of the 1400 MHz Flare Emission..." by G.D. Holman, J. Bookbinder and L. Golub, in Radio Stars, eds. Gibson and Hjellming, Proc. Conf. on Stellar Continuum Radio Astron., Boulder (1984).

ON STELLAR X-RAY EMISSION

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I. INTRODUCTION

The past five years have seen the emergence of an entirely new astronomical discipline, stellar x-ray astronomy. It lies at the crossroads of a number of apparently disparate astronomical research areas:

(a) Solar physics: Stellar x-ray astronomy constitutes the major testing ground for theories of stellar surface activity which have been developed over the past two decades in the solar context. Stellar observations allow one to test predictions regarding the dependence of activity level on stellar parameters which cannot be varied in the course of observations restricted to the Sun. These parameters include stellar age, the mean stellar rotation rate, the depth of the convection zone, and stellar surface characteristics such as surface effective temperature, effective gravity, and elemental abundances.

(b) Stellar physics: The stellar surface activity which underlies the observed x-ray emission provides the means by which stellar spindown and mass loss occur. Until the advent of x-ray observations, other proxy indicators of stellar activity (such as Ca II H and K emission; Wilson 1966, 1978) proved to be insufficiently sensitive to provide the large volume-limited samples of

stars throughout the Hertzsprung-Russell diagram which are required for systematic and unbiased study of the full range of possible stellar activity levels (as opposed to study of only the most active examples). The presence of such surface activity also has important implications for more traditional studies of stellar properties, such as determinations of surface elemental abundances and stellar age (Duncan 1981; Soderblom 1983, 1984); this occurs because surface activity on the Sun is now known to modulate the measurement of abundances for important species such as Lithium (cf., Giampapa 1983).

(c) General Astrophysics: Because of the particle and mass ejections which accompany stellar surface activity, stars provide one of the main sources of mass input to the interstellar medium (ISM), and may provide at least some of the input source particle spectrum for galactic cosmic rays (see review by Montmerle 1984). The observed x-ray emission not only provides a primary diagnostic for the presence and level of such activity (and in principle allows determination of the elemental abundances of the source material for the ejected matter), but also figures as an important source of ionizing flux in the immediate stellar neighborhood (especially in regions of star formation). It is also thought that stellar activity levels modulate the accretion rate in low-mass compact binary systems such as cataclysmic variables (Rappaport, Verbunt, and Joss 1983; Spruit and Ritter 1983; Patterson 1984); that the x-ray emission from young stars may play an important role in the chemical state of the ISM in star-forming regions (viz., Feigelson 1983); that the x-ray emission from low-mass main sequence stars can contribute significantly to the galactic component of the diffuse soft x-ray background (Rosner et al. 1981; Bookbinder et al. 1984); and, finally, that the physical processes which figure in stellar surface activity (e.g., magnetic dynamo activity, magnetic reconnection, buoyancy, flaring, wind mass loss, etc.) provide an interpretational framework for other astrophysical systems in which such processes are thought to occur (e.g., Rosner 1982).

These major developments in stellar x-ray astronomy follow on the heels of a similarly major readjustment in our understanding of solar surface activity, which resulted primarily from the wealth of data gathered by the Skylab ATM instruments over a decade ago (see reviews by Withbroe and Noyes 1977; Vaiana and Rosner 1978; and the monographs of the Skylab Workshops, edited by Zirker [1978], Sturrock [1980], and Orrall [1981]). Since then, it

has become clear that the entire range of solar coronal activity is governed by the interaction between the surface magnetic fields of the Sun and the ambient plasma; thus, magnetic fields play a central role in the energetics of not only solar flares (as has been long realized), but also of the far more quiescent "Quiet Sun". The physical processes which control local conditions -- hydrodynamics, heat conduction, radiation, mechanical heating by waves and currents -- involve the complications of microscopic plasma effects well-known to the laboratory plasma physicist, albeit under a vastly different combination of physical conditions and spatial scales. In addition, processes less familiar to the laboratory physicist -- stochastic magnetic dynamo activity, magnetic flux concentration by turbulent fluids, magnetic buoyancy -- must be considered. These microscopic and macroscopic processes undoubtedly also play a central role in the physics of activity on other stars, as well as in the physics of rather different astrophysical systems, such as the interstellar medium, supernova remnants, accretion disks, and similar (but possibly still more "exotic") objects. In many of these cases, the lack of spatial resolution mitigates against direct confrontation of theories with observations; the astrophysicist must instead rely upon extrapolation from (analogous) cases in which theory and observations can be compared relatively directly. Thus, solar and stellar physics can play a central role in the interpretation of plasma phenomena in distant astronomical objects.

The emergence of stellar x-ray astronomy as a new astrophysical discipline has also played a central role in the recent resurgence of interest in the "solar-stellar connection". This resulted from the serendipitous conjunction of stellar x-ray observations provided by the now-defunct Einstein Observatory (Vaiana et al. 1981; Helfand and Caillault 1982; Linsky 1982; Vaiana 1982, 1983; Golub 1983a, b; Haisch 1983; Johnson 1983a; Stern 1983; Serio 1984), the renewed exploitation of ground-based Ca II observations (Wilson 1978; Vaughan et al. 1982), the spectroscopic stellar observations from the International Ultraviolet Explorer (Dupree 1982, 1983; Linsky 1982, 1983), and the increased sensitivity in radio observations made possible by the VLA (viz., Gibson 1984; Dulk 1985). This confluence has led to substantial synergism, in that methods of analysis first developed in one of these contexts have been rapidly exploited in the others; the studies of the variation of activity levels with various stellar attributes (such as

rotation) are the most prominent example of this synergism.

In this review, we shall focus on the main physics problems which arise when confronting the stellar x-ray data. We shall not examine the details of the data, except insofar as such studies lead us directly to an important physical issue; we will instead refer the reader to the specific literature (including the large number of available reviews of the data) where such details are provided. A central issue throughout our review is the extent to which the extrapolation from solar physics is justified, and to define (if possible) the limits to such extrapolation. This issue is of particular concern as one confronts x-ray emission from stars which are not traditionally thought to be "solar-like" (such as OB stars and T Tauri stars): while the stellar astronomer "bred" in the solar context may be tempted to apply the "solar analogy", those who have focussed on the physics of such stars may have radically-different notions as to the origin of the x-ray emission (even if its presence has come as a great surprise to such workers!).

II. THE BASIC PROPERTIES OF X-RAY EMISSION FROM STARS

Observations of quiescent x-ray emission from stars were first made in the middle 1970's (Catura, Acton, and Johnson 1975; Mewe et al. 1975), and the EXOSAT satellite is currently acquiring both imaging and spectroscopic data on such emission (viz., Landini et al. 1984a, b; Mewe 1984; Westergaard et al. 1984). Nevertheless, virtually all of the published data to date on stellar x-ray emission have been obtained from two satellites, the first High Energy Astronomy Observatory (HEAO 1) and the Einstein Observatory (HEAO 2). Arguably the most dramatic impact has been made by images acquired from the latter instrument, and much of this review will focus on the observational and theoretical implications for our understanding of solar and stellar activity which have emerged from these results. Because of the wealth of reviews in the literature which summarize the observational details (Rosner and Vaiana 1979; Linsky 1980, 1982, 1983a, b; Vaiana 1980, 1981a, b, 1982; Mewe, Schrijver, and Zwaan 1981; Golub 1983a, b; Johnson 1983a; Stern 1983; Cassinelli and McGregor 1984; Serio 1984), we will not emphasize the minutiae

of the observations, but rather focus on the major observational questions, the outstanding observational problems, and the theoretical implications of the data now in hand.

What ought to be expected from stellar x-ray observations if the Sun is a prototypical late-type dwarf star? The visually dramatic change in the observed solar activity level seen during the declining phase of the solar activity cycle by the *Skylab* soft x-ray telescopes corresponds to a change of well below an order of magnitude in energy output at soft (~ 1/4 keV) x-ray wavelengths; and if one takes the full variation of coronal radiative output (excluding flares) during the course of an entire activity cycle into account, then one would expect roughly a factor of ten variation in the stellar soft x-ray luminosity (Pallavicini *et al*. 1981). As is now well-known, this is not at all what is observed: if the Sun were really prototypical, the *Einstein* Observatory stellar surveys would have been meager affairs. Instead, the Sun lies near the bottom end of the *observed* range of x-ray luminosities of late-type stars, which spans over three decades. This fundamental result is vividly displayed by the stellar x-ray luminosity functions for late spectral type dwarf stars discussed below: clearly, the Sun's coronal luminosity is very modest when compared to that of other stars.

The basic observational facts regarding the level of x-ray emission are simply summarized in the H-R diagram of Figure 1, and by the cumulative x-ray luminosity functions displayed in Figure 2 (for the basic observational data, see references to the surveys and observational reviews cited above, as well as those cited specifically below):

(1) The data are consistent with *all* dwarf stars of spectral type dF through dM being x-ray emitters, with quiescent luminosities ranging between roughly 10^{26} and 10^{31} ergs sec^{-1}

(2) *All* stars earlier than (roughly) B5 are x-ray emitters, at emission levels ranging between 10^{29} to 10^{34} ergs sec^{-1}, with a roughly constant x-ray-to-bolometric luminosity ratio of ~ 10^{-7} (Harnden *et al*. 1979; Seward *et al*. 1979; Long and White 1980), independent of luminosity class.

(3) There is a narrow spectral range -- from roughly B8 to A5 -- on the

main sequence for which there is no credible evidence for any x-ray emission from spectroscopically normal stars and Am stars (Golub et al. 1982; Schmitt et al. 1984); however, there is evidence for x-ray emission from Ap stars (see also Cash and Snow 1982).

(4) Late spectral type giants and supergiants experience a cutoff in x-ray emission levels as one moves to later spectral type (Ayres and Linsky 1980; Ayres et al. 1981; Vaiana et al. 1981; Haisch and Simon 1982); the nature and location of this cutoff is discussed further below.

(5) Pre-main sequence stars are very vigorous x-ray sources, and show a definite trend of decreasing mean emission levels with nominal stellar age (Feigelson 1983; Maggio et al. 1984; Micela, Sciortino, and Serio 1984; Micela et al. 1985; Caillault and Helfand 1985).

(6) The x-ray spectra of late-type stars are thermal, with single-component temperatures ranging between 10^6 to several times 10^7 K; however, there is considerable evidence that a single-component analysis is not an adequate description of spectra for sources with sufficient count statistics (Holt et al. 1979; Swank et al. 1981; Mewe et al. 1982; Swank and Johnson 1982; Vedder and Canizares 1983; Schrijver, Mewe, and Walter 1984), and that a continuous emission measure distribution in temperature is far more appropriate (Majer et al. 1984; Mewe 1984; Schmitt 1984a; Schmitt et al. 1984a).

(7) As would be expected from solar-like activity behavior, late-spectral type main sequence stars (Haisch et al. 1980, 1983; Kahler et al. 1982) and evolved stars in close binary systems (e.g., the RS CVn's; viz., Walter et al. 1980; Agrawal et al. 1983) show episodic highly transient behavior in x-rays; indeed, very young main sequence and pre-main sequence stars show the most dramatic range of such behavior (Stern 1982; Montmerle et al. 1983; see especially Stern, Underwood, and Antiochos 1983 for comparisons). In contrast, early spectral type stars show little evidence for such short time scale variability, but do show evidence for longer-period fluctuations (e.g., Collura et al. 1984). We shall not consider variability, especially of the flare or transient type, any further in this review, and instead refer the reader to the reviews of Haisch (1983), Gibson (1983), Charles (1983), and

Mullen (1983).

(8) X-ray emission levels from close binary systems, such as the RS CVn (viz., Walter et al. 1980) and the W UMa stars (viz., Cruddace and Dupree 1984), in which accretion is not thought to play a major role, are nevertheless substantially enhanced over that from effectively single stars whose classical stellar characteristics (e.g., mass, radius, effective temperature) are similar to those of the individual binary components (see reviews by Charles 1983; Dupree 1983; Linsky 1984).

III. THE SOLAR ANALOGY AND THE MODELING OF X-RAY EMISSION FROM LATE-TYPE STARS

The first issue to be dealt with is how the x-ray data just summarized are to be interpreted. If we confine our attention to the observations of late spectral type stars, then the obvious candidate analogue is the solar corona: however, if such extrapolation is to make sense at all, then it ought to be the case that canonical stellar activity indicators other than x-ray emission have plausible counterparts in the solar data; and that, conversely, the kinds of correlations between such indicators seen on the Sun are also observed to hold in the stellar data.

Perhaps the best place to start is with a brief reminder of what the Sun looks like when viewed at a variety of wavelengths; the extensive full-disk x-ray image catalogue of Zombeck et al. (1979) gives perhaps the best overview to date. From such images, it is evident that -- even on the immediate, qualitative level -- the intensity of x-ray emission is very inhomogeneous, and correlates rather well spatially with emission from lower-temperature species, as well as with the photospheric magnetic field (Vaiana and Rosner 1978 and references therein). Furthermore, it is evident that the spatial contrast of activity levels becomes greater as the observational wavelength decreases: minimal in the optical, and maximal in the x-ray (the extremes -- hard x-rays and gamma rays -- are extremely localized, and are seen virtually only during the course of solar flares). This variation of contrast with wavelength is illustrated by the composite shown as Fig. 6 in Vaiana and

Rosner (1978), and allows us to conclude that the activity contrast is greatest at precisely those wavelengths at which most of the radiative emission from a hot plasma -- the chromosphere and corona -- occurs. Unfortunately, the terrestrial atmosphere is strongly absorbing at these wavelengths, and it is therefore not totally surprising that, prior to about 1975, there were no direct observations of steady coronal activity from solar-like stars (e.g., Mewe 1979; Ulmschneider 1979): it was not until roughly after that date that space-borne telescopes of sufficient sensitivity at short wavelengths became available.[1] Until then, studies of stellar

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[1] This difficulty was of course readily circumvented (at least partially) by finding signatures of solar surface activity which (i) can be seen at wavelengths accessible to ground-based observers, and (ii) can be detected in spatially-integrated light (i.e., if one views the Sun as a stellar-like point source; viz., Skumanich et al. 1984). If such signatures exist, then, as pointed out above, it is in principle possible to test whether stars show the kinds of correlations between activity indicators observed on the Sun; sensible extrapolation from solar physics hinges on a positive result. Indeed, a variety of such indicators exist, ranging from modulation of the integrated stellar light in the visible (due to "spots"; e.g., Oskanyan et al. 1977; Willson et al. 1981) to emission in the Ca II H and K lines (Wilson 1966, 1978; Vaughan 1983) and in He 10830 A (Zirin 1975, 1982). The observed correlations between these ground-based activity indicators are what one would expect on the basis of solar observations, and so the assumption that what we are observing indeed can be understood by extrapolation from the Sun appears to be on solid ground. More recently, these ground-based studies have received renewed impetus because of the exploitation of high-resolution optical spectroscopy to detect the Zeeman splitting of magnetically-sensitive lines (Robinson, Worden, and Harvey 1980; Marcy 1983), allowing the kind of correlative studies of coronal and photospheric activity which have been successfully carried out for the Sun (viz., Vaughan 1984).

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activity relied upon ground-based proxy indicators for stellar activity -- modulation of integrated light, Ca II H and K emission, and observations of the He 10830 line -- which indeed strongly supported the very attractive

proposition that solar-like surface activity is not peculiar to the Sun alone. However, it must be kept in mind that ground-based diagnostic tools share the common defect that their very visibility from ground is evidence for rather non-solar behavior: that is, if we were to view the Sun as a star, and place it at typical stellar distances, little regarding the properties of solar activity could be deduced on the basis of these three classical ground-based diagnostics -- solar activity is simply not sufficiently vigorous. The use of ground-based diagnostics has thus the effect of selecting a very special sub-class of stars, namely those which show presumably solar-like activity behaviour, but to an extreme; and we therefore run the substantial risk of biasing our conclusions regarding the general behavior of stellar surface activity.

These kinds of selection effects ought to be avoidable if the sample of stars considered is volume-limited, rather than flux-limited. In order to maximize the size of the sample, one ought therefore observe stellar activity at those wavelengths at which the hot plasma emits most of its energy; and, with sufficient sensitivity, one is then in a position to explore a significant portion of the coronal luminosity function (i.e., the probability distribution function for the coronal luminosity)[2]. In this way, one might

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[2] A crucial aside is that in conducting such volume-limited surveys, it is essential to consider both the detections <u>and</u> the upper limits (e.g., failures to detect); one can then use so-called "detections-and-bounds" (Avni <u>et al</u>. 1980; see Rosner 1983 for details on applications to stellar observations) or "survival analysis" (Schmitt, Golub, Harnden, and Rosner 1984; Schmitt 1984b; Feigelson and Nelson 1985; Schmitt and Rosner 1985) methods in order to construct maximum likelihood distribution functions for stellar x-ray parameters. In particular, Schmitt, Golub, Harnden, and Rosner (1984) have shown by example that disregard of the detection upper limits can lead to conclusions entirely opposite to those reached by considering the full set of information available.

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hope to observe the full range of possible stellar activity levels, and minimize selection effects. Thus, if the Sun is to be any guide, one ought to

observe stellar activity most optimally at UV and shorter wavelengths. In saying this, one must of course be prepared for the possibility that plasma temperature regimes associated with stellar activity are rather different than is the case for the Sun: the difference in solar coronal temperatures of the Quiet Sun and coronal holes as deduced by, for example, soft x-ray diagnostics (e.g., Maxson and Vaiana 1977) should stand as an important warning. Indeed, definition of the domain of applicability of the "magnetically-confined" corona prototype is itself a central problem of stellar activity modeling, particularly for late-type giants and supergiants (viz., Dupree 1982; Linsky 1982).

Let us then assume that we have obtained a relatively bias-free set of observations of stellar coronal emission, and ask how the data are to be interpreted. If we again confine our attention to stars of late spectral type, then the natural starting point is the basic fact of the structuring of the (solar) corona. The existence of coronal structures, and the important role played by magnetic fields in such structuring (which is most obvious in solar active regions) was recognized long before high resolution EUV and x-ray images were available (see, for example, Billings and Saito 1964). However, the availability of on-disk observations of the corona in the EUV and in x-rays revealed the ubiquitous loop structuring of the emitting regions throughout the solar corona, as well as the close connection with regions of strong surface magnetic fields (Vaiana, Krieger, and Van Speybroeck 1970). A series of rocket flights led to semi-empirical modelling of coronal loop structures and coronal magnetic fields (Vaiana, Krieger, and Timothy 1973); and the long duration Skylab missions permitted study of the temporal evolution of the emission regions in the corona, and of the quantitative link between magnetic fields and coronal emission.

These data show the solar corona to be the superposition of a variety of coronal structures, whose physical parameters (size, temperature, density) cover a wide range (see Withbroe and Noyes 1977), and whose relation to the topology of the defining magnetic fields is quite strict: virtually all of the coronal emission comes from topologically closed magnetic structures (Van Speybroeck, Krieger, and Vaiana 1970; Vaiana, Krieger, and Timothy 1973; McIntosh *et al.* 1976), with regions of topologically open magnetic fields characterized by severely lowered x-ray fluxes (Maxson and Vaiana 1977). In

all of the following discussion, we will assume that if the solar analogy applies, then the high temperature plasma seen in x-ray emission from stars is in fact predominantly confined in such topologically closed loop structures.

The importance of structuring in coronal physics was put on a firm theoretical foundation in the late 1970's (Rosner, Tucker and Vaiana 1978; Rosner and Vaiana 1978; Craig, McClymont, and Underwood 1978; Vesecky et al. 1979; see also Priest 1981, Withbroe 1981, and Hammer 1983): the key realizations were, first, that the coronal magnetic fields associated with individual loop structures physically confined the plasma (so that mass loss to the solar wind is insignificant for these structures) and, second, that these loops could be considered as relatively independent "mini-coronae" because of the thermally-insulating effect of the confining magnetic fields (Landini and Monsignori-Fossi 1975). Thus, the solar corona can be viewed -- at any given time -- as an ensemble of these building blocks whose precise statistical mix of physical properties (size scale, mean field strength, mean plasma temperature and pressure) is determined by the stochastic eruption of magnetic flux from the solar interior (Vaiana and Rosner 1978). That is, the emerging solar surface fields most certainly play a passive role in determining the coronal topology (and thus determine the confinement properties of the coronal gas); in addition, they may also play an active role by providing the direct means for dissipation of mechanical energy flux to heat the coronal plasma in situ (Gold 1964; Tucker 1973; Rosner, Tucker, and Vaiana 1978; Ionson 1978; see reviews by Wentzel 1978 and Kuperus, Ionson, and Spicer 1981, and the more recent work of Parker 1983a,b). These various considerations have a remarkably simple consequence to lowest order in the physical description of such structures: if we consider the balance between only local heating (by whatever means), thermal conduction, and (optically-thin) radiatiative losses in a hydrostatic (confined) plasma, one directly obtains a testable scaling relation involving the observable quantities loop length, (peak) coronal temperature, and loop pressure (Rosner, Tucker, and Vaiana 1978; Craig, McClymont, and Underwood 1978). In concert with more sophisticated observations, these scaling relations can be adumbrated to include more physics, such as gravitational stratification (Serio et al. 1981; Wragg and Priest 1981) and steady flows (viz., review by Priest 1981), but the essential element remains: the coronal plasma is a bright source of x-ray emission because of magnetic confinement. Thus, the first point to recognize

when discussing observations of x-ray emission from solar-like stars is that the observed emission very likely derives from a statistical mix of structures, so that any attempts to describe the observations by appealing to a "mean" atmosphere must be viewed with some trepidation.

Given the extremely complicated mixture of loop structures which are found in the solar corona, can spatially unresolved stellar observations (which necessarily average over the entire ensemble of structures in a stellar atmosphere) be of any real use in studying the nature of stellar activity and, more specifically, the coronal heating mechanism? Here nature has been kind to us, in that it is now clear that variability in emission properties is a common feature of stellar x-ray emission; the hope is then to use the variability as a probe of the kind of structuring to be expected in stellar coronae.[3] The observed variability is of course not surprising, since the

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[3] The outstanding exception to this is the use of eclipses in relatively close binary systems to disentangle the geometric relationship between different coronal components, as has been illustrated by the study of the eclipsing RS CVn system AR Lac by Walter, Gibson, and Basri (1983; see also White *et al.* 1984).

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solar corona is known to be variable on a remarkable wide range of time scales (even when flares are excluded), as is well-illustrated in the sequential x-ray images of the Sun published by Zombeck *et al.* (1979); these sequences show five solar rotations observed from *Skylab*, and demonstrate that on essentially any time scale of interest -- from minutes, hours, and days to months -- the Sun may be regarded as a variable x-ray source. These variations have a wide dynamic range: thus, an example of a rather dramatic variation is seen during the fourth and fifth rotations, when the corona varied from a solar maximum-like configuration to one more characteristic of a solar minimum-like configuration during a time span of less than seven days. However the full variation in coronal composition during different portions of the solar cycle is even more extreme than that: for example, x-ray data obtained near solar minimum show an entirely different kind of corona, which is dominated by large numbers of small active regions (the so-called

"ephemeral active regions"). These small regions are short-lived, do not develop sunspots and have relatively low x-ray emission measure, but are found to contain as much magnetic flux as the larger, longer-lived active regions found at times of higher solar activity (Golub 1980).

These solar coronal variations can be quantified by representing the variation of the total emission by a superposition of the various known atmospheric components, and by accounting both for the solar cycle variation of each component, and for the evolutionary histories of the different types of emerging field regions associated with these coronal plasma constituents. From quantitative studies of this kind, Golub (1983) concluded that the average solar corona is dominated by a single type of structure approximately half of the time. That is, at solar maximum, the entire coronal x-ray emission can be characterized by the properties of large active regions, with a temperature (T) of approximately $10^{6.6}$ K and an emission measure (EM) of approximately $10^{50.5}$ cm^{-3}. At solar minimum, the corona is characterized by the small emission regions (together with their diffused -- evolved -- states), with T approximately $10^{6.3}$ K and EM approximately 10^{49} cm^{-3}. This then suggests that it may be possible to describe the morphology of stellar coronal emission by superposition of a minimal number of distinct emission components, especially if models are further constrained by combining the x-ray data with contemporaneous observations of the cooler underlying atmosphere (cf., Mewe and Zwaan 1980; Ayres, Marstad, and Linsky 1981; Pallavicini et al. 1982; Schrijver et al. 1983; Giampapa et al. 1985). As we shall discuss below, there is in fact some evidence that such a minimal multi-component description is an apt summary of the stellar x-ray data.

These preliminaries allow us to place x-ray observations of late-type stars into an interpretational framework which is well-tested. However, it may well be that this (solar) analogy is inappropriate, and hence it is essential to continually devise observational tests to verify its applicability. The most prominent example of how the exact solar analogy may fail for a "solar-type" star is AR Lac: Walter, Gibson, and Basri (1983) have in fact shown that significant x-ray emission comes from regions well-removed from the stellar surfaces of the two binary companions in this system, so that a model of "interacting loops" (in which the magnetospheres of the two companions interact to produce local heating, and hence x-ray emission; Uchida

and Sakurai 1983; Uchida 1984) may be a far more appropriate description of the source morphology.

IV. MODELING X-RAY EMISSION FROM EARLY-TYPE STARS

In contrast to the case of late-type stars, we do not have ready access to a nearby astronomical object which shares its stellar properties with that of the hot stars; it is therefore not entirely surprising that the relative state of our understanding of the outer atmospheres of early spectral type stars is quite primitive when compared with that of solar-type stars. Since this subject area is hardly mature, we will confine ourselves to a very brief review of the principal physics issues; and refer the reader to the recent reviews by Cassinelli (1984) and Hearn (1984) for further details.

Studies of possible x-ray emission from the atmospheres of early-type stars proper (as opposed to, for example, the terminal shocks associated with their winds) which preceeded the definitive detection of soft x-rays from these stars (Harnden et al. 1979; Seward et al. 1979) focussed on models which were essentially analogues of the solar atmosphere in extremis: a hot corona near the stellar surface, underlying a far cooler high-speed wind (Cassinelli and Olsen 1979). It is by now apparent that this kind of model, as well as its various variants (Rosner and Vaiana 1980; Stewart and Fabian 1981; Cassinelli 1984; Uchida 1984; Waldron 1984; Underhill 1984) cannot easily reconcile the observed extinction (at energies below roughly 0.5 keV) and the spectrum (whose derivation is dominated by photons with energies above approximately 0.5 keV) derived from the x-ray data with the imputed wind mass column densities derived from radio and IR observations (see Cassinelli et al. 1981 for details). That is not to say that, by invoking sufficient complexity for this class of models, an acceptable fit to the data cannot be achieved; instead, the real difficulty is to account in a natural and plausible way for the presence of any plasma heating in the first place -- to appeal to, for example, the solar paradigm of magnetic and/or wave heating is not easily physically motivated, and hardly accounts in a natural way for one of the principal observational constraints, namely the remarkably constant x-ray-to-bolometric luminosity ratio as a function of spectral type.

An alternative physical picture of what might be occuring was proposed by Lucy and White (1980; also Lucy 1982), who revived earlier suggestions by Lucy and Solomon (1970), Hearn (1975), Nelson and Hearn (1978), and McGregor, Hartmann, and Raymond (1979) that the massive radiatively-driven wind might be unstable (see also Carlberg 1980; Kahn 1981; Owocki and Rybicki 1984), and argued that the higher-density "blobs" formed as a result of the instability would lead to the formation of shocks (and associated high-energy radiative emission) throughout the unstable region of the wind outflow. The advantages of this model are several: (i) it is now indisputable that the radiatively-driven winds of OB stars are indeed linearly unstable to density perturbations (thus overcoming a principal objection to the corona-wind model); (ii) shock-heated matter is expected to be distributed throughout the wind, thus substantially easing the difficulty of reconciling the observed wind mass column densities and soft x-ray extinction; (iii) the emission is expected to be naturally time-variable, as it is the superposition of emission from many distinct shocked regions of the wind. This latter expectation is indeed in accord with observations of variability at x-ray wavelengths (Collura <u>et al</u>. 1984).

However, we do not believe that this subject is as yet closed because several major gaps still separate the observations from a reasonably-complete model:

(i) Although linear instability has been demonstrated, the non-linear development of the instability to the point of "blobs" (or their effective equivalent) remains to be studied;

(ii) The simple phenomenological shock model (in which the shock strength is fixed) does not in fact give a good account of the x-ray data (Cassinelli and Swank 1983); what is required is a distribution of shock strengths, which must at this juncture remain entirely <u>ad hoc</u> (because no theory of shock formation, which evolves the flow non-linearly from the linear domain, exists at present).

Resolution of these various issues will unquestionably involve (in addition to the theoretical work just alluded to) a substantial effort at

multi-wavelength observations (see, for example, Caillault et al. 1985 and White and Becker 1983), preferably carried out with (near-) simultaneity in order to correlate emission levels and variability over the entire range of wavelengths in which non-thermal emission has been observed. In addition, the *Einstein* observations provided a tantalizing hint that higher spectral resolution and sensitivity (especially below 1 keV) could provide decisive tests of extant models (viz., Cassinelli and Swank 1983).

V. THE PHYSICS OF STELLAR X-RAY EMISSION

The most obvious question which the data discussed above engenders is simply why stars emit x-rays. The answer to this question is not straightforward, and indeed for the early spectral type stars cannot as yet be reliably answered. Our understanding of the x-ray emission processes for the late spectral type stars is heavily dependent upon the applicability of the solar analogy discussed in the previous section; and, in so far as this analogy applies, we do understand much of the basic physics leading to stellar x-ray emission.

(i) Correlation Between Stellar X-ray Emission and Other Stellar Attributes.

The first question is simply observational: given the large dispersion in emission levels for stars of any given spectral type and luminosity class (Figure 2), can we determine which physical attributes of stars account for the observed variance? Thus, because the total x-ray luminosity appears to be only very weakly related to the effective surface temperature (and hence to the level of surface fluid turbulence) for late-type main sequence stars, some stellar properties which do not figure in placing a star in the H-R diagram must determine the actual emission levels (this is not the case for the early spectral type stars, as discussed below).

As posed, this issue is a classical statistics problem (common factor analysis), with the not inconsiderable complication that the data is heavily censored (e.g., contains many upper bounds).[4] What these missing parameters

[4] Indeed, some work in applying classical common factor analysis to data which are only weakly censored (and so for which the upper limits -- which were ignored -- carry only a very limited amount of information) has been carried out by C. J. Schrijver (1982), who showed that for the limited sample he considered, stellar rotation was the dominant factor in determining the level of stellar x-ray emission; see also Majer *et al.* (1984) in the context of the "rotation-activity connection" for RS CVn stars.

might be was suggested early on by *HEAO 1* observations (Walter *et al.* 1980) and subsequent *Einstein* Observatory surveys (Walter and Boywer 1981) of *RS CVn* stars, which suggested that rotation is a significant determinant of coronal luminosity for these binary systems; we shall return to this particular issue below. Such a connection between rotation and *chromospheric* activity level was long known from Ca II data (Kraft 1967); and discovery of a coronal luminosity-rotation correlation for isolated and effectively single late-type dwarf stars followed from analysis of the *Einstein*/Center for Astrophysics (CfA) stellar survey data (Pallavicini *et al.* 1981, 1982). In contrast, it was evident from the first observations of x-ray emission from early spectral type stars that the dominant determinant of emission levels was the bolometric luminosity (Harnden *et al.* 1979; Seward *et al.* 1979; Long and White 1980); thus, for these stars, the location in the H-R diagram is indeed a very good predictor of x-ray emission levels.

(a) *Stellar x-ray emission and stellar rotation.*

The basic points regarding the correlation of x-ray emission levels with rotation rate are summarized in Figure 4, which represents an update of the data presented by Pallavicini *et al.* (1981): the rotation dependence of coronal emission for stars of spectral type F7 to M5, and luminosity classes III, IV and V, is quite clear. The linear best fit to the total data sample is based on detections alone, and indicates that L_x is proportional to the square of the stellar rotation rate. In contrast, the early-type stars do not show any rotation dependence of x-ray emission levels (Pallavicini *et al.* 1981). Some controversy has occurred regarding the precise slope of the power

law relation connecting L_x and the rotation period (cf., Walter and Boywer 1981; Pallavicini et al. 1981, 1982; Rengarajan and Verma 1983; Rengarajan 1984), but it appears that the fundamental difficulty (which remains in place to date) is the introduction of possibly large biases because of the ill-defined nature of the various samples of stars for which both rotation rates and x-ray luminosities are known. We also note that similar difficulties beset determination of a correlation between the stellar activity level and characteristic Rossby number (viz., Noyes et al. 1984), discussed further in the next section: as emphasized by Schmitt, Golub, Harnden, and Rosner (1985), such correlations using x-ray data must be very cautiously interpreted, especially if no account is taken of the presence of upper bounds in measurement of x-ray luminosity, stellar rotation rate, or both (cf., Mangenay and Praderie 1984; Marilli and Catalano 1984).

For one class of late-type stars, it has however been possible to conduct a systematic study of the relation of stellar rotation to surface activity: the RS CVn stars. These stars form a class of binaries whose components tend to be somewhat evolved; their orbital periods are generally less than about 14 days (Hall 1976), although it is common to include much longer-period systems in this category (such as Capella). By comparing the x-ray to bolometric luminosity ratio L_x/L_{bol} with the rotation periods of these systems (which correspond to the orbital periods in the synchronous shorter-period systems), Walter and Boywer (1980) showed that this ratio varied as $(\text{period})^{-1.2}$. The class of stars examined is however quite heterogeneous, and one must therefore ask whether some other stellar attribute could possibly lead to this correlation; this possibility was raised by Pallavicini et al. (1981), who pointed out that L_x was not correlated with period for this sample of stars, but that the bolometric luminosity was. This problem has been studied in detail by Rengarajan and Verma (1983), who have shown that the bolometric luminosity is indeed related to the orbital period as $(\text{period})^{0.7}$ for a much larger sample of F, G, and K eclipsing binaries (cf., Young and Koniges 1977), and as $(\text{period})^{1.24}$ for the more restricted Walter and Boywer sample; hence it appears that essentially all of the correlation between L_x/L_{bol} and period is due to the correlation between L_{bol} and period, a conclusion which has been further strengthened by a formal principal component analysis of the RS CVn data which explicitly shows that there is no significant "rotation-activity" correlation for these stars (Majer et al. 1984). Indeed, the correlation

between L_{bol} and period is to be expected because of the simple fact that for tidally-coupled close binaries, the stellar radius is roughly proportional to the stellar separation, so that -- via Kepler's law -- there is a correlation between bolometric luminosity and orbital (and hence rotation) period; see Young and Koniges (1977).

(b) Stellar x-ray emission and stellar age.

A most basic question is whether stellar activity levels show any evolutionary effects as a given star moves along its track in the H-R diagram, from protostellar object of well-evolved giant or supergiant. This question has been systematically addressed by several extensive surveys of stellar clusters and associations, ranging from T Tauri associations (Ku and Chanan 1979; Feigelson and Kriss 1981; Montmerle et al. 1983) to the classic nearby young open clusters Hyades (Stern et al. 1981; Zolcinski et al. 1982), Pleiades (Helfand and Caillault 1982; Micela, Sciortino, and Serio 1984; Micela et al. 1985; Caillault and Helfand 1985), and Ursa Majoris (Walter et al. 1984).

Let us begin by considering the youngest stellar objects. During the final phases of star formation, a contracting protostar is enveloped in a shroud of accreting gas, so that until recently, this phase of stellar birth was invisible to us (viz., Gertz, Black, and Solomon 1984). However, it had been speculated by theorists that such objects might be x-ray sources, and hence observable in spite of the large obscuration in the optical: thus, Bisnovatyi-Kogan and Lamzin (1977) suggested that if the outer atmospheres of T Tauri stars were expanding outward (e.g., in the form of a stellar wind), and are thermally-driven, then a necessary consequence would be the presence of a hot (million degree) corona near the base of the outflow region; the corresponding x-ray luminosity would then be of order 10^{34} erg sec^{-1}. Further x-ray emission would be also expected from the collision between this outflow and the ambient interstellar matter (viz., Schwartz 1978). In contrast, if the atmospheres of such stars were dominated by accretion from the ambient interstellar matter, then one might expect emission due to the impact of the accreting matter on the stellar surface (viz., Ulrich 1976; Mundt 1981), with the temperature of the impact-heated matter largely determined by the infall speed. The difficulty with these various predictions is that they were

largely contradicted by the earliest observational studies: thus, observations by ANS and SAS-3 resulted in the detection of only one source which could be associated with one cr more pre-main sequence objects (den Boggende et al. 1978; Bradt and Kelley 1979), but whose luminosity was clearly far below that supposed by Bisnovatyi-Kogan and Lamzin (1977), and whose source spectrum was quite a bit harder than one would expect for the accretion models. It is from this historical perspective that the striking Einstein Observatory data from the Orion Nebula (Ku and Chanan 1979; Ku et al. 1982), the Taurus-Auriga complex (Gahm 1980; Feigelson and DeCampli 1981; Walter and Kuhi 1981, 1983), the Rho Ophiuchi cloud (Montmerle et al. 1983), and the Chamaeleon cloud (Feigelson and Kriss 1981) must be viewed.

These Einstein observations showed, first, that pre-main sequence stars without question constitute a new class of soft x-ray sources; second, that their emission -- when seen -- is of order 1,000 times more vigorous than that of main sequence stars of similar spectral type; third, that their emission is extremely variable; fourth, that the level of x-ray emission is correlated with the stellar optical magnitude, but not with the classic indicators of pre-main sequence "activity" (such as H alpha emission); and, fifth, that the spectrum is cut-off at low energies (as is expected from absorption by the intervening matter within the star-forming region), and seems to be intrinsically hard (for a stellar source). These observations, which are reviewed in much greater detail by Feigelson (1983), raise a number of immediate questions:

What is the origin of the x-ray emission? The basic question to be answered is how apt the "solar analogy" really is for these stars. Can one regard the observed x-rays as the radiative emission from solar-like activity centers, or is the observed emission more properly regarded as the entire consequence of continual "flaring"? That is, while there is no doubt that substantial transient activity does take place (most beautifully shown by the results of Montmerle et al. 1983), there is considerable question whether a less-variable "background" atmosphere is present. It is especially intriguing that this notion of continual very small-scale flaring as the ultimate coronal heating process has been again raised as a possibility for the Sun itself (viz., Lin et al. 1984). In order to answer these questions in the case of very young stars, it is necessary to (i) place strong constraints on the x-ray

spectrum of the observed emission (in order to isolate the relative locations of the x-ray emitting matter and the cooler plasma associated with pre-main sequence stellar surface activity); (ii) determine the extent of variability (in order to determine whether flaring can entirely account for the observed emission); and (iii) determine a bound on the level of "quiescent" emission which is comparable to that of more evolved late-type stars.

What is the ultimate cause of the activity? Closely related to the above question is the problem of accounting for the underlying cause of "activity" stars. If, as in the case of late-type stars, the activity (whether transient or not) is the result of magnetic activity on the surface of these stars, then one would expect a similar sensitivity to the characteristics of the rotation characteristics and the convective interiors of these stars. In order to test these expectations, it is necessary to establish the x-ray luminosity functions for these very young stars in a variety of star formation regions, and then to explore their correlations with the rotation rate distribution, spectral type distributions, and age of the cluster stars; this program remains for the future, so that this question must remain unanswered at present.

What happens once stars pass out of the protostellar phase? A most useful comparison involves observations of the two classic nearby open clusters, the Pleiades (Caillault and Helfand 1985; Micela et al. 1984, 1985) and the Hyades (Stern et al. 1981; Westergaard et al. 1984) by the Einstein Observatory. Figure 4 gives the basic result: comparison of the cumulative x-ray luminosity functions for G stars in the Pleiades and Hyades open clusters, and for field G stars, shows a clear decline in activity levels with age. This result is as one would expect on the basis of the by now classical picture of the evolution of stellar activity: as the star evolves, its surface activity leads to spindown, and hence reduced surface activity, lowered spindown rate, and so forth (Biermann 1946; Schwarzschild 1948; Schatzman 1962; Skumanich 1972; Kraft 1967). However, this scheme is complicated by the fact that the data argue against a simple monotonic decline in activity levels. The particular problem is raised by the relative inactivity of both the K and M stars in the Pleiades; indeed, there are no definitive detections of M dwarf stars in this open cluster. This puzzle is compounded by the fact

that the rotation rates of the Pleiades K stars are anomalously high (Stauffer et al. 1984).

Stauffer et al. and Micela et al. (1985) argue that this anomaly can be understood by tracing the detailed evolution of the internal rotation profile of these stars as they descend to the main sequence. That is, rapid evolution on the radiative track should lead to spin-up of the entire star (with modest radial differential rotation), followed by rapid spindown (by magnetic braking) of the outer (visible) convecting envelope (leading to significant differential rotation between the outer envelope and the radiative core; cf., Endal and Sofia 1981, and especially Tassoul and Tassoul 1984); the internal rotation profile in the latter case is particularly suited for vigorous magnetic dynamo activity (Rosner 1980; Spiegel and Weiss 1980; Golub et al. 1981; Schussler 1983). Hence, since the Pleiades K stars are thought to fall in the former category, and the G stars in this cluster in the latter category, the dominance of G star activity can be understood.

(c) Stellar x-ray emission and spectral type.

For stars ranging from spectral type early O to roughly B5, the level of x-ray emission is proportional to the stars' bolometric luminosity; the proportionality constant is approximately 10^{-7} (see Pallavicini et al. 1981, and references therein). A transition between this "early spectral type" behavior, and the behavior of later spectral type stars (whose emission levels dominantly depend on rotation rate) occurs in the mid-A spectral type range (Schmitt et al. 1984); the coincidence between the location of this transition and the location of the onset of surface convection leads to the obvious suggestion that surface convection is indeed the necessary prerequisite for solar-like stellar activity (see also Bohm-Vitense and Dettmann 1980).

Other than the aforementioned transition stage from "early-type" behavior, late spectral type stars generally do not show any evidence for a primary dependence of x-ray emission levels on spectral type; this fact is best illustrated by the sequence of x-ray luminosity functions for distinct spectral types shown in Figure 2. However, a major exception to this conclusion occurs at the cool end of the main sequence: as shown in Figure 5a, the is some evidence that the mean x-ray emission levels of dwarf M stars

drops as one moves beyond approximately dM5 (Golub 1983a), a phenomenon which has its counterpart in H alpha observations of such stars (Giampapa 1983). This suggestion has been recently investigated by Bookbinder et al. (1984), who have shown for a volume-limited sample of dM stars that such a decrease in emission levels does indeed occur.[5]

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[5] Rucinski (1984) has also recently considered this problem, and has come to a seemingly opposite conclusion (i.e., that the luminosity ratio L_x/L_{bol} does not significantly decrease within the spectral type range M0-M6). In fact, there is no contradiction. Rucinski based his analysis on the sample of stars considered by Johnson (1983b); indeed, his Figure 1 closely resembles Figure 5a shown here. As just discussed, the entire effect Bookbinder et al. (1984) find is due to the severe depletion of both detections and upper limits for spectral types later than roughly M5. Thus, Rucinski's analysis is perfectly valid for the detected stars; and his disregard of upper limits and of the observational decrease in the discovery rate (in either detection or upper bound on the x-ray emission level) of very low-mass stars makes his analysis not relevant to the larger question of whether late-type stars as a class (i.e., not just restricted to the known emitters) experience a decrease in activity level at roughly spectral type M5.

The argument runs as follows. Figure 5a does not demonstrate the decrease in x-ray emission levels directly because of possible (and likely) selection effects; however, if we assume that the mass function for late-type stars remains roughly constant beyond M5 (Bahcall and Soneira 1980), then this figure does show that the x-ray observations are "missing" stars later than M5. That is, since this Figure shows all the data based on beating optical proper motion survey data against the x-ray observations (and thus includes detections as well as upper bounds), and since the sum total of detections and upper bounds for stars later than M5 is below expectations based on a constant mass function, it must be that this comparision of the x-ray and optical data has missed a substantial number of stars. Because the residual number of unidentified x-ray detections in the Einstein fields cannot make up this deficit, one is forced to conclude that either the missing stars have emission

levels below the thresholds of the typical Einstein fields, or the stellar mass function drops steeply at approximately M5V. The latter possibility cannot be ruled out, but in any case, the upper bound on the luminosity of the "missing" stars leads to the inevitable conclusion that the stars later than approximately M5 (if they exist in any numbers) must have substantially-reduced x-ray emission levels.

(d) Stellar x-ray emission and effective gravity.

A particularly striking aspect of Figure 3 is that stars of all luminosity classes fall on the same regression line of x-ray luminosity versus rotation rate, indicating that stars which rotate and have outer convection zones emit x-rays at levels independent of effective gravity (the only major exceptions being the cool giants and supergiants, to be discussed below). In contrast, the x-ray data showed from the first observations that for early spectral type stars, effective gravity does play a role; that is, because effective gravity correlates with bolometric luminosity (and as the bolometric and x-ray luminosities are observationally correlated), the effective gravity is perforce correlated with the x-ray luminosity. However, since theory does expect a relation between bolometric luminosity and x-ray emission levels (at least for those models which invoke instabilities in radiation-driven winds; see recent review articles in Underhill 1984), the correlation between x-ray luminosity and effective gravity for these stars is best regarded as secondary, and (in and of itself) of no physical interest. Unfortunately, a more detailed theoretical account of the x-ray emission from such stars has as yet proved elusive, and remains a significant task for the future.

The theoretical situation is hardly better as one moves toward cooler spectral type stars. The early Einstein Observatory data already showed that late spectral type giants and supergiants are at best very weak x-ray sources (Ayres and Linsky 1980; Vaiana 1981a, b; Vaiana et al. 1981; Haisch and Simon 1982). This dearth of x-ray emission from evolved cool stars remains as an outstanding puzzle. One popular proposal has been to invoke an analogy with solar coronal holes: in such regions, the coronal gas streams out to form the solar wind, and the level of x-ray emission is severely depressed (cf., Maxson and Vaiana 1977; and the reviews in Zirker 1977). Since the evolved stars in question are known to be vigorous sources of low terminal speed, high mass

flux winds (see reviews by Dupree 1982, Hartmann 1983, MacGregor 1983, Brown 1984, and references therein), and as the boundary line in the H-R diagram defining the onset of high mass loss rates very roughly corresponds to the boundary line separating stars which have and have not been detected in x-rays (as well as in other indicators of high-temperature matter above the stellar surface; Linsky and Haisch 1979; Ayres and Linsky 1980; Simon, Linsky, and Stencel 1982), this coronal hole analogy has seemed quite apt (see also Cassinelli and McGregor 1984).

The dangers in drawing this analogy too closely are severe however. First, it remains true that there is no commonly-accepted theoretical account for solar coronal holes, e.g., a first-principles theory which links a presumptive source of energy and momentum (such as magnetohydrodynamic waves) to the observed solar wind mass flux and wind speed at 1 AU, and to the observed temperature and density in the inner corona of the source coronal hole (see especially Leer, Holzer, and Fla 1982 for a general discussion of this problem, and Holzer, Fla, and Leer 1983 for details on the inadequacy of Alfven wave-driven wind models in the stellar case; see also MacGregor 1983). The coronal hole analogy hence is perforce purely phenomenological. Second, the dearth of x-ray emission from these evolved stars is far more profound than in the solar case: for example, the upper bounds on the stellar surface x-ray flux for several late spectral type supergiants lie over three orders of magnitude below that of solar coronal holes (Vaiana et al. 1981). This suggests a profound difference in the structures of the wind atmospheres of the Sun and these evolved stars -- the steep témperature rise into the corona characteristic of the Sun seems to be suppressed in these far more slowly accelerating winds. Thus, the challenge of understanding the physics of these atmospheres lies in reconciling the large mass loss and low terminal speeds (which imply that the bulk of the flow heating and acceleration occurs relatively close to the star, and below the wind sonic point) with the absence of a temperature rise (which in turn implies either small heating rates below the sonic point, or very effective cooling) -- a completely different agenda for theory than that faced by the solar physicist. Thus, to put it in its best light, the solar coronal hole analogy for explaining the lack of emission from late spectral type evolved stars remains an interesting idea.

(ii) The Physical Characteristics of Stellar Coronae.

Because of the essential lack of spatial resolution, it should not be surprising that the extent to which the physical attributes of the plasma(s) which produce stellar x-rays can be deduced is severely limited. Consider first the coronal temperature. Even the rather modest energy resolution of the Einstein Observatory Imaging Proportional Counter (IPC) allowed the conclusion that single-component temperature models for stellar x-ray spectra are generally inadequate (at least for data with high signal-to-noise). The spectroscopic IPC results of the Einstein/CfA stellar surveys show that one can grossly characterize coronal temperatures by a bimodal temperature distribution, with peaks in this distribution at log T ~ 6.3 and log T ~ 7.0 (Vaiana 1983; Schmitt 1984; Majer et al. 1984). Somewhat higher resolution spectra obtained by the Einstein Observatory Solid State Spectrometer (SSS) shows similar bimodal distributions, but with a shift in temperature: typically, the IPC low-temperature component is not found by the SSS analysis, but instead a somewhat high-temperature (log T > 7.5) appears (Holt et al. 1979; Swank et al. 1981; Swank and Johnson 1982); while the relatively high resolution spectroscopic data obtained from the Einstein Observatory Objective Grating Spectrometer (OGS) for Capella (Mewe et al. 1982) and from the EXOSAT OGS (Mewe 1984) seem more consistent with the IPC data.

These results can be reconciled in the following way (Majer et al. 1984): any given coronal loop structure must be characterized by an internal temperature distribution, and hence by a fractional distribution of matter (the differential emission measure; Jordan 1976; Withbroe 1975) as a function of temperature. Furthermore, as in the Sun, it is likely that there is a superposition of loops with different mean properties (i.e., length, mean temperature, mean gas pressure). The result is a convolved differential emission measure distribution, which for a spatially-unresolved steady source cannot be "deconvolved" into its component constituents (i.e., there is no a priori method for distinguishing the contributions of the internal run of temperatures within given loops from that of distinct closed structures with different mean temperatures).[6] In any case, the ultimate consequence for a

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[6] If the coronal emission varies with time, it may be possible to distinguish between different emission components (e.g., if the temporal variations have a

strong spectral dependence); a nice example of this possibility is provided by studies of the coronal emission measure distribution on RS CVn stars (viz., Golub 1983a; Walter, Gibson, and Basri 1983; White et al. 1984; and the review by Charles 1983, and references therein). Another possibility of disentangling geometry already alluded to is based on correlations between coronal x-ray emission and emission from cooler parts of the atmosphere (viz., Mewe and Zwaan 1980; Ayres, Marstad, and Linsky 1981; Pallavicini et al. 1982; Schrijver et al. 1983; Giampapa et al. 1985), but the lack of simultaneity of these observations, in concert with the everpresent variability in emission levels, have limited use of this technique to date.

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moderate energy resolution instrument is the detection of a multi-component temperature distribution; quite typically, the number of such components corresponds to the number of well-distinguished spectral "windows" the spectrometer has (the IPC had two, centered at roughly 0.2 and 1.5 keV, respectively). Thus, the data lead to the conclusion that the coronae of late-type stars are characterized by a broad range of plasma temperatures, from $\log T \sim 6.0$ to > 7.5.

Consider next the amount of emitting material, and its density. A glance at the functional form of the plasma cooling function (viz., Raymond and Smith 1977) shows that it varies roughly as $T^{-1/2}$ in the temperature range of interest to us, and with the square of the electron density; hence the cooling function varies at most by a factor of 3-5 due to the temperature variation alone. This immediately implies that the great observed variation in stellar x-ray luminosity is largely due to a variation in the amount of coronal material present. Since large-amplitude variations in x-ray luminosity outside of flares are rare, it is reasonable to assume that the emitting matter is distributed fairly homogeneously over the stellar surface. Hence the emitting volume is roughly fixed, and we can reasonably conclude that the large range of observed x-ray luminosity levels reflects a (somewhat more modest) variation in mean coronal density; this is precisely the case for the Sun (viz., Vaiana and Rosner 1978), as the modulation of coronal intensity within a given coronal loop structure is dictated essentially entirely by the variation in coronal loop density.

(iii) The Basic Physical Questions

Can we understand the correlation between stellar x-ray emission and rotation for late-type stars, and between x-ray emission and bolometric luminosity for early-type stars? It is probably fair to say that there is now a consensus answer to the former question, at least on the qualitative level, but that a commonly-accepted model for x-ray emission from early-type stars is still out of reach. In the following, we briefly outline the basic model for stellar activity of late-type stars, and refer the reader to the still-developing literature on coronae of early-type stars (see especially the volume edited by A. B. Underhill 1985, the recent work of Owocki and Rybicki 1984, and references therein).

The basic notion underlying current models of stellar activity is that in a rotating star having an outer convection zone, coupling of rotation and convection with ambient magnetic fields can lead to a regenerative magnetic dynamo (whose ultimate driving energy source is of course the outward-flowing thermal flux due to nuclear burning at the stellar core; viz., Parker 1979); these dynamo-generated magnetic fields inevitably rise to the surface of the star because of magnetic buoyancy (viz., Acheson 1978; Schmitt and Rosner 1983). These surface magnetic fields are still embedded in a fluid -- the surface of the solar convection zone -- in which the hydrodynamic forces dominate (high-beta), and hence are continually subjected to "jostling" by turbulent surface fluid motions. This "jostling" of the emerged fields can lead to plasma heating (for recent views, see Kuperus, Ionson, and Spicer 1981; Priest 1983; Parker 1983a,b), with the result that a corona confined by the emerged magnetic fields is formed; the emission from this corona is presumably seen in the Einstein and EXOSAT x-ray images.

To what extent can one improve upon this qualitative description? A truely first-principles theory, which starts with the dynamical equations for stellar structure and magnetic flux generation and dissipation, and attempts to predict x-ray emission levels as a function of, say, stellar mass, age, and rotation rate, is at present out of reach. One obvious stumbling block is our still meager understanding of non-linear dynamo theory, which does not allow us to predict with any degree of certainty the rate of magnetic flux production on stars, including the Sun (cf., Gilman 1983; Schussler 1983).

Nevertheless, there does exist a vast body of solar observations from which properties of solar-type dynamos may be deduced (or at least constrained). That is, although the dynamo itself is not directly accessible to observations, we can observe samples of the magnetic fields that are produced in the interior, and are brought to the surface by the joint action of magnetic buoyancy and convection. The question is then whether the observable characteristics of the emerging fields show regularities which may constrain theory. Such studies have been conducted (cf., Golub et al. 1980; Zwaan 1980; Howard and LaBonte 1983; Giampapa and Rosner 1984; Vaughan 1984), and suggest the following picture of a solar-type dynamo.

There are abundant reasons for believing that the dynamo is located rather near to the bottom of the solar convection zone, either in the bottom layers of the convection zone itself (Parker 1979), or in a thin stably-stratified undershoot layer separating the convection zone proper from the radiative core (Rosner 1979; Spiegel and Weiss 1980, 1982; Golub et al. 1981; van Ballegooijan 1982; Schmitt and Rosner 1983; Schmitt, Rosner, and Bohn 1984). These reasons include the short time scale for buoyant rise of flux throughout most of the convection zone (too short for efficient dynamo action to proceed; Parker 1979; Acheson 1978; 1979); the effect of topological pumping in pushing magnetic flux downwards in the turbulent convection zone (Drobyshevski and Yuferev 1974; Arter 1983); the increased efficiency of dynamo action within a boundary layer separating regions of stable and unstable entropy stratification (Bullard and Gubbins 1977); and the possibility of stabilization of magnetic buoyancy modes in such a convectively-stable layer (Schmitt and Rosner 1983). If this is an appropriate model for the dynamo, there are a number of immediate deductions which follow when extrapolating to other stars:

(1) For stars which are expected to be fully-convective on the basis of standard stellar interiors models, the boundary layer necessary for dynamo action would not exist; naively, one would thus predict that stellar activity ought to decrease dramatically at the point at which stars become fully-convective on the main sequence (although in the presence of interior magnetic fields, it is not clear that such a star would ever become fully convective). Indeed, a significant reduction in stellar activity levels is observed on the main sequence at approximately M5, the point at which such

stars are expected to become fully convective (but see discussion of this point above).

(2) For stars with very shallow convection zones, the major effect is likely to be a significant reduction in the typical size scale of surface activity regions (Giampapa and Rosner 1985); this result is a consequence of the shift to larger wavenumbers of the most unstable magnetic buoyancy modes (Schmitt and Rosner 1983). Again, observations (in the visible, in the UV continuum, and in x-rays) show that roughly blueward of the spectral type at which the steep reduction in convection zone depth occurs on the main sequence, both activity itself (Bohm-Vitense and Dettmann 1980; Schmitt, Golub, Harnden, and Rosner 1985), and the amplitude modulation of activity (a measure of the spatial scales of surface inhomogeneities; see Giampapa and Rosner 1984 and references therein) show a steep decline.

(3) For stars of fixed spectral type, an increased gradient in differential rotation at the base of the convection zone ought to have the consequence of significant enhancement in activity levels. As just discussed above, precisely such an effect appears to be present when comparing the activity levels of G and K stars in the Pleiades open cluster (Micela et al. 1984, 1985).

(4) One of the basic expectations of classical dynamo theory is that the efficiency of magnetic flux production is a sensitive function of the ratio of the stellar rotation period to the convection overturning time scale (Durney and Latour 1978); this ratio (the Rossby number) enters physically because it is the Coriolis force that ultimately is responsible for the production of meridional magnetic flux from the emerging toroidal magnetic flux. Indeed, Noyes et al. (1984) have shown that there exists an excellent correlation between Ca II H and K emission strength and the Rossby number for solar-type stars (see also Mangenay and Praderie 1984 and Marilli and Catalano 1984). A more exacting test (because of the wide range of depths of the outer convection zone) is to consider the rotation-activity correlation for main sequence stars in the spectral type range A0-F7. Thus, Schmitt, Golub, Harnden, and Rosner (1985) have shown, first, that the correlation between rotation rate and x-ray emission levels is virtually absent when either this full spectral type range, or subranges, are considered; but, second, that

within the restricted subrange of F stars, there is some evidence (as yet weak) for a correlation between Rossby number and activity levels. This seeming contradiction (which needs to be further explored by the coming generation of more sensitive x-ray telescopes) is precisely what is to be expected from a population of stars with a wide range in both rotation rates and convection zone depths, but for which a "rotation-activity connection" does hold (because the large variation in convection zone depths would mask any correlation between rotation rate and activity level).

VI. STELLAR X-RAY EMISSION IN THE MORE GENERAL ASTROPHYSICAL CONTEXT

In addition to providing information on the physics of the outer layers of stars, stellar x-ray emission -- and stellar activity in general -- also plays significant roles in the larger galactic context, some of the more important of which we now very briefly discuss.

(a) X-ray Emission from Stars and the Diffuse Soft X-ray Background

The most straightforward consequence of stellar x-ray emission is its passive role in contributing to the galactic component of the diffuse soft x-ray background (Gorenstein and Tucker 1976; Rosner et al. 1981). This effect is demonstrated in Figure 6 (taken from Bookbinder et al. 1984), which shows the contribution of very late spectral type dwarf stars to the number density of soft x-ray sources as a function of detection threshold, and the derived contribution to the soft x-ray background (as deduced by using a spatial distribution for such stars derived by Bahcall and Soneira 1980). Comparison of Figure 6 with the results of Rosner et al. (1981), who used a simple exponential model for the stellar distribution, shows that the main conclusions remain intact: stars seem to provide approximately 20% of the diffuse galactic component of the soft x-ray background in the ~ 1/4 keV energy range. These results also show why it is essential that the next generation of very sensitive x-ray telescopes must have high spatial resolution: at a sensitivity threshold level of 10^{-16} ergs cm^{-2} s^{-1} within the the Einstein Observatory energy passband, we expect to see about 100 dM stars per square degree!

(b) X-ray emission From Very Young Stars and the Local Interstellar Medium

In addition to the above "passive" role played by stellar x-ray emission, it may also play an "active" role in significantly effecting the physics of the interstellar medium in the immediate vicinity of stars. This possibility has been explored most prominently in the case of very young x-ray-active objects, such as are found in star formation regions: the possible effects which have been only tentatively explored to date include the regulation of star formation by the stellar x-ray emission (as a result of the large flux of ionizing photons emanating from these objects embedded in molecular cloud regions; see Lepp and McCray 1983; Krolik and Kallman 1983; Silk and Norman 1983); the resulting increased coupling of the accreting gas to ambient magnetic fields (Silk and Norman 1983; Shu and Terebey 1984) implies that de-coupling of the accreting flow from the retarding cloud magnetic fields is no longer determined by the thermal history of the accreting gas viewed in isolation (viz., Shu and Terebey 1984, and references therein). In addition, these observations raise the question as to how important stellar "activity" was in the formative stage of the solar system and during the formative stages of planetary atmospheres (cf., Sekiya, Hayashi, and Nakazawa 1981; Canuto et al. 1982; Feigelson 1982; Zahnle and Walker 1982).

(c) Mass and Particle Input to the Interstellar Medium

Activity at the surface of stars is known to lead to at times vigorous ejection of matter from the gravitational confines of stars, either in the form of massive wind outflows (see reviews by Cassinelli 1979, Cassinelli and McGregor 1984) or transients (which themselves can lead to bulk mass ejection and relativistic particle production; viz., Coleman and Worden 1976). As a consequence of these particle and mass ejections, stars provides one of the main sources of mass input to the interstellar medium (viz. Abbott 1982 and Van Buren 1984), and may provide at least some of the input source particle spectrum for cosmic rays (either directly via the injection of particles accelerated during stellar flares (viz., Mullan 1979; see also Gorenstein 1981), or indirectly via particle acceleration at shocks lying either within the winds themselves, or at the termination shock of the winds (viz., Cesarsky

and Montmerle 1983). The latter possibilities are strongly supported by evidence that the elemental composition of galactic cosmic rays heavier than He is very similar to that of solar energetic particles (Meyer 1981, 1985); a recent summary of the current situation is provided by Montmerle (1984).

VII. CONCLUSIONS AND FUTURE PROSPECTS

Our understanding of spatially unresolved astrophysical systems suffers from the twin difficulties that the source geometry is not obvious, and that the relevant physical description is not necessarily unique; these two problems lie at the heart of the difference between astrophysics and the terrestrially-based physical sciences. From this perspectice, stellar x-ray astronomy (at least as regards late spectral type stars) has the great advantage that solar observations can be used both to constrain the physics and to suggest the appropriate observational tools: the Sun and its environs provide us with a directly observable laboratory for studying the magnetohydrodynamics and plasma physics which must enter into the physics of stellar x-ray emission, and allow us to define the theoretical framework within which we interpret the observations. The major results which have been gained from such studies are new constraints on models for stellar activity, which demand tests of theoretically-predicted dependences of activity levels with stellar parameters which cannot be varied by studying the Sun alone. Thus, stellar x-ray observations, and the attendent modeling, have already provided additional constraints on both theories of coronal heating and magnetic flux generation (i.e., dynamo theory) which cannot be obtained independently from solar work.

In the larger astrophysical context, observations of stellar x-ray emission allow us to more sensibly extend the solar analogy to more "exotic" (and certainly astrophysically interesting) phenomena, such as the formation of coronae on accretion disks and the energetics of hot galactic halos. Such extensions are not restricted to studies of late-type stars: certainly, an understanding of possible instabilities in radiation-driven winds of OB stars will provide the necessary underpinnings for any attempts to apply such theories to, for example, instabilities in radiation-driven jets.

Where does the future of x-ray observations of stars lie? A strong hint of the most fruitful lines of research is easily gleaned by considering the major outstanding observational problems, each of which is intimately tied to a major theoretical problem of stellar activity:

(a) What is the nature of the emission from early spectral type stars? That is, at present neither the true source spectrum, nor the nature of the low energy cutoff seen in low and moderate resolution spectra, are well-understood. At issue here is the physical location of the x-ray-emitting matter (especially relative to the stellar wind outflow), and whether the observed emission is best regarded as a remote analogue of solar magnetic surface activity -- a corona -- at or very near the stellar surface (Hearn 1972; Cassinelli and Olson 1979; Rosner and Vaiana 1980; Stewart and Fabian 1981; Cassinelli 1984; Uchida 1984; Waldron 1984; Underhill 1984), or as a consequence of instabilities in the massive radiation-driven winds (Lucy and Solomon 1970; Hearn 1975, 1984; Nelson and Hearn 1978; McGregor, Hartmann, and Raymond 1979; Carlberg 1980; Lucy and White 1980; Lucy 1982; Owocki and Rybicki 1984). These problems will be directly addressed as multi-wavelength observations of the nonthermal activity of such stars proceed (cf., Caillault et al. 1985; White 1985; and references therein), and at x-ray wavelengths will require the kind of very high sensitivity, high resolution spectroscopy which currently-planned instruments such as AXAF will permit. High sensitivity is essential because the nearest subject stars lie roughly 400 pc from us, and have x-ray luminosities of order $10^{30} - 10^{32}$ ergs sec^{-1}; this implies photon-limited observations for the kind of high resolution ($> 10^{3}$) spectroscopy needed to address the above problems.

(b) Do very late spectral type giants and supergiants emit any x-rays? The lack of x-ray detections of such stars suggest that either they do not emit x-rays (or do so only at levels substantially below solar values), or that extinction (by, for example, stellar wind material) is so prohibitive that there is no significant emergent x-ray flux. The basic question here is whether the solar analogy with coronal holes (regions of sharply-reduced x-ray emission which are the sources of the solar high speed wind streams) is appropriate, so that the lack of observed emission accurately reflects an absence of any x-ray emitting matter (Ayres and Linsky 1980; Dupree 1982;

Linsky 1984). The future observational requirements are thus to better constrain the x-ray spectra of stars near the "dividing line" (Linsky and Haisch 1979) in the H-R diagram (in order to test for a softening of the spectra upon reaching the dividing line, and to search for a soft cut-off which may result from the presence of intervening cool wind plasma); and to obtain far stronger upper limits on the possible emission levels of late spectral type giants and supergiants. Translated into instrumental terms, the observational needs are again for high resolution, high sensitivity spectroscopy and for very high sensitivity, high spatial resolution imaging.

(c) Do normal main sequence stars in the spectral type range approximately B5-A4 emit any x-rays? Present observations show that x-ray levels of such stars (if they emit at all) must lie substantially below the median level of solar-type stars, and that a steep rise in emission levels occurs in parallel with the sharp growth in depth of the outer convection zone as one moves down the main sequence past spectral type approximately A4 (a boundary line whose precise location predicted by stellar interiors models is sensitive to the value of the mixing length parameter -- the ratio of the mixing length to the local scale height). However, the upper bounds on x-ray emission levels for late B and early A dwarf stars do not lie very much below solar emission levels, and it is of great interest to place much tighter constraints on the possible emission levels: we want to know to what extent stellar activity has as a necessary prerequisite a convective stellar surface (which the stars in question are presumed not to have). The key observational requirement in this case is clearly sensitivity; at a limiting flux of 10^{-16} ergs sec^{-1} cm^{-2} (which will be easily accomplished by AXAF), future observations will be able to place an upper limit on the coronal x-ray luminosity of the nearest candidate stars of less than log L_x ~ 23.5, more than a factor of 1,000 below the typical solar x-ray luminosity.

(d) What is the nature of the x-ray emission from young (pre-main sequence) stars? Thus, as is the case for the early spectral type stars, at present we know neither what the true source spectrum is, nor what the nature of the low energy cutoff seen in low resolution spectra is. Furthermore, the nature of the observed strong variability is highly uncertain (although an argument based on the flare energy-frequency histogram suggests a solar flare analogy; Montmerle et al. 1983; Rosner and Vaiana 1978). Here the central

problems are to what extent the solar analogy applies; whether there is any quiescent component; whether the emission is best seen as (solar) flare-like; and to what extent the observed "activity" is the result of a (regenerative) dynamo process, as opposed to the decay of primordial fields. Again, high resolution spectroscopy appear essential to answering the question of the structure of the emitting regions. Furthermore, because these objects typically lie in regions of large obscuration at soft x-ray wavelengths, and as their spectra are somewhat harder than those of main sequence stars of comparable spectral type, there is considerable reason to study these objects with imaging telescopes capable of high sensitivity at energies above 2-3 keV (imaging is essential because the projected number density of objects in star-forming regions can lead to severe source confusion at angular resolutions as good as 1').

(e) Is the dearth of x-ray-bright (active) M dwarf stars later than approximately M5 a reflection of a fundamental change in dynamo behavior for fully convective stars, or is it simply that these "missing" stars are truely missing? If the latter is the case, then the mass function at the low-mass end of the main sequence must steeply decline past roughly M5, with major implications for either theories of low-mass star formation, or for models of stellar evolution (which commonly predict a very slow descent to the main sequence -- and hydrogen burning -- for these stars). From the x-ray point of view, the key task is to probe the solar neighborhood for very low-luminosity stellar objects; if the "missing" stars do exist, then one would expect to find them in such "deep" surveys. The key observational requirements are for high sensitivity and high angular resolution imaging; the latter requirement is borne of the fact that the optical counterparts to the sought-for x-ray sources will be very faint stars ($m_V > 22$), so that source identification will be extremely difficult unless the source position error circle is sufficiently small (i.e., of order an arc second, or less).

(f) Is the transient component of stellar x-ray emission a reflection of a fundamentally distinct plasma heating process? As discussed above, transient emission appears to dominate the x-ray output of some classes of stars, and in fact constitutes the entire emission from pre-main sequence stars observed to date. Because the frequency distributions of flares generally show a power law dependence on total flare energy or peak flux for

many classes of transient sources (viz., Rosner and Vaiana 1978), it is not at all obvious whether such transients contribute significantly to what is normally referred to as the quiescent emission component: the crucial question is then whether there is a lower energy cutoff on this power law. There is some indication from observations of solar hard x-ray emission that such a cutoff (if it exists) may lie at sufficiently low flare energies that the total energy associated with fast electrons produced in "microflares" is a significant fraction of the total coronal x-ray luminosity (viz., Lin et al. 1984). If this is the case, then the traditional distinction between transient and quiescent energy release and plasma heating disappears, and we will have to regard stellar flares as simply the extreme high energy tail of a continuous distribution of coronal energy release events. Whether this is in fact the case remains to be established, and it is clearly solar observations that will provide the definitive resolution to this problem.

These few examples should make it plain that it is indeed both spectroscopy and very high sensitivity and spatial resolution imaging which are essential to the construction of activity models more complex than the simple models discussed to date. It is likely that the next generation of x-ray telescopes (such as a modified ROSAT, or NASA-sponsored high-throughput missions) and facilities (i.e., AXAF) will indeed carry out the necessary observations.

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Literature Cited

Abbott, D. C. 1982. Ap. J. 263: 723.

Abbott, D. C., Bieging. J. H., and Churchwell, E. 1984. Ap. J. 280: 671.

Achson, D. J. 1978. Phil. Trans. Roy. Soc. London A. 289: 459.

Agarwal, P. C., Rao, A. R., Riegler, G. R., and Stern, R. A. 1983. In Proc. 18th Int. Cosmic Ray Conf. Bangalore, India (Vol. I).

Allen, C. W. 1973. Astrophysical Quantities. London: Athlone Press.

Avni, Y., Soltan, A., Tananbaum, H., and Zamorani, G. 1980. Ap. J. 238: 800.

Ayres, T. R., and Linsky, J. L. 1980. Ap. J. 235: 76.

Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L., and Rosner, R. 1981. Ap. J. 250: 293.

Ayres, T. R., Marstad, N. C., and Linsky, J. L. 1981. Ap. J. 247: 545.

Bahcall, J. N., and Soneira, R. M. 1980. Ap. J. Suppl. 44: 73.

Belcher, J. W., and Olbert, S. 1975. Ap. J. 200: 369.

Biermann, L. 1946. Naturwiss. 33: 118.

Billings, D. E., and Saito, K. 1964. Ap. J. 140: 760.

Bisnovatyi-Kogan, G. S., and Lamzin, S. A. 1977. Sov. Astron. 21: 720.

Bohm-Vitense, E., and Dettmann, T. 1980. Ap. J. 236: 560.

Bonnet, R. M. and Dupree, A. K. 1981. Editors, Solar Phenomena in Stars and Stellar Systems. Dordrecht: Reidel.

Bookbinder, J., Golub, L., Schmitt, J. H. M. M., and Rosner, R. 1984. BAAS, 16: 515.

Bradt, H. V., and R. L. Kelley 1979. Ap. J. Lett. 228: L33.

Brown, A. 1984. In Cool Stars, Stellar Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 282. New York: Springer.

Brown, A., and Jordan, C. 1981. M.N.R.A.S. 196: 757.

Bullard, E. C., and Gubbins, D. 1977. Geophys. Astrophys. Fluid Dyn. 8: 43.

Butler, C. J., Byrne, P. B., Andrews, A. D., and Doyle, J. G. 1981. M.N.R.A.S. 197: 815.

Caillault, J.-P. 1982. Astron. J. 87: 558.

Caillault, J.-P., and Helfand, D. J. 1985. Ap. J., in press (Feb. 1985).

Caillault, J.-P., Chanan, G. A., Helfand, D. J., Patterson, J., Nousek, J. A. et al. 1985. Nature, in press.

Canuto, V. M., Levine, J. S., Augustsson, T. R., and Imhoff, C. L. 1982. Nature 296: 816.

Carlberg, R. G. 1980. Ap. J. 241: 1131.

Cash, W., and Snow, T. 1982. Ap. J. Lett. 263: L59.

Cassinelli, J. P. 1979. Ann. Rev. Astron. Astrophys. 17: 275.

Cassinelli, J. P. 1984. In The Origins of Non-Radiative Energy and Momentum in Hot Stars. A. B. Underhill, editor.

Cassinelli, J. P. 1983. In Solar Wind V, M. Neugebauer, editor, p. 263. NASA CP-2280.

Cassinelli, J. P., and MacGregor, K. 1984. In Physics of the Sun, P. Sturrock, D. M. Mihalas, T. E. Holzer, and R. K. Ulrich, editors.

Cassinelli, J. P., and Olsen, G. L. 1979. Ap. J. 229: 304.

Cassinelli, J. P., and Swank, J. H. 1983. Ap. J. 271: 681.

Cassinelli, J. P., Waldron, W. L., Sanders, W. T., Harnden, Jr., F. R., Rosner, R., and Vaiana, G. S. 1981. Ap. J. 250: 677.

Catura, R. C., Acton, L. W., and Johnson, H. M. 1975. Ap. J. Lett. 196: L47.

Cattaneo, F., Jones, C. A., and Weiss, N. O. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 307. Dordrecht: Reidel.

Cesarsky, C. J., and Montmerle, T. 1983. Space Sci. Rev. 36: 173.

Chanan, G. A., Ku, W. H.-M., and Charles, P. 1979. BAAS 11: 623.

Charles, P. A. 1983. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 415. Dordrecht: Reidel.

Cohen, M., and Kuhi, L. V. 1979. Ap. J. Suppl. 41: 743

Coleman, G. D., and Worden, S. P. 1976. Ap. J. 205: 475.

Collura, A., Sciortino, S., Serio, S., and Rosner, R. 1984. In Symp. X-ray Astronomy 84, Bologna, Italy, in press.

Craig, I. J. D., McClymont, A. N., and Underwood, J. H. 1978. Astron. Astrophys. 70: 1.

Cruddace, R. G., and Dupree, A. K. 1984. Ap. J. 277: 263.

de Loore, C., and De Jager, C. 1970. In IAU Symposium 37, Nonsolar X-ray and Gamma-Ray Astronomy. L. Gratton, editor, p. 238. Dordrecht: Reidel.

den Boggende, A. J., Mewe, R., Gronenschild, E. H., and Grindlay, J. E. 1978. Astron. Astrophys. 62: 1.

Drobyshevski, E. M., and Yuferev, V. S. 1974. JFM 65: 33.

Dulk, G. 1985. Ann. Rev. Astron. Astrophys., in press.

Duncan, D. K. 1981. Ap. J. 248: 651.

Dupree, A. K. 1982. In Advances in UV Astronomy: Four Years of IUE Research, Y. Kondo, J. M. Mead, and R. D. Chapman, editors, p. 3. NASA CP-2238.

Dupree, A. K. 1983. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 447. Dordrecht: Reidel.

Durney, B. R., and Latour, J. 1978. Geophys. Astrophys. Fluid Dyn. 9: 241.

Endal, A. S., and Sofia, S. 1981, Ap. J. 243: 625.

Feigelson, E. D. 1984. In Cool Stars, Stellar Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 27. New York: Springer Verlag.

Feigelson, E. D., and DeCampli, W. M. 1981. Ap. J. Lett. 243: L89.

Feigelson, E. D., and Kriss, G. A. 1981. Ap. J. Lett. 248: L35.

Feigelson, E. D., and Nelson, P. I. 1985. Ap. J., in press.

Gahm, G. F. 1980. Ap. J. Lett. 242: L163.

Galloway, D. J., and Weiss, N. O. 1981. Ap. J. 243: 945.

Gary, D. E., and Linsky, J. L. 1981. Ap. J. 250: 284.

Gertz, R. D., Black, D. C., and Solomon, P. M. 1984. Science 224: 823.

Giampapa, M. S. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 187. Dordrecht: Reidel.

Giampapa, M. S., and Golub, L. 1982. Editors, Cool Stars, Stellar Systems, and the Sun. Washington, D.C.: Smithsonian SP-392.

Giampapa, M. S., Golub, L., Peres, G., Serio, S., and Vaiana, G. S. 1985. Ap. J., in press.

Giampapa, M. S., and Rosner, R. 1984. Ap. J. Lett. 286: L19.

Gibson, D. M. 1983, In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 273. Dordrecht: Reidel.

Gilman, P. A. 1982. In Cool Stars, Stellar Systems, and the Sun, M. S. Giampapa and L. Golub, editors. Washington, D.C.: SAO Report 392.

Gilman, P. A. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 247. Dordrecht: Reidel.

Gold, T. 1964. In Symp. on Physics of Solar Flares, W. Hess, editor (NASA SP-50), p. 389.

Golub, L. 1980. Phil. Trans. R. Soc. London A 297: 595.

Golub, L. 1982. In Cool Stars, Stellar Systems, and the Sun, M. S. Giampapa and L. Golub, editors, p. 39. Washington, D.C.: Smithsonian SP-392.

Golub, L. 1983a. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 345. Dordrecht: Reidel.

Golub, L. 1983b. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 83. Dordrecht: Reidel.

Golub, L., Maxson, C. W., Rosner, R., Serio, S., and Vaiana, G. S. 1980. Ap. J. 238: 343.

Golub, L., Rosner, R., Vaiana, G. S., and Weiss, N. O. 1981. Ap. J. 243: 309.

Golub, L., Harnden, Jr., F. R., Pallavicini, R., Rosner, R., and Vaiana, G. S. 1982. Ap. J. 253: 242.

Golub, L., Harnden, Jr., F. R., Rosner, R., Vaiana, G. S., and Cash, W. 1983. Ap. J. 271: 264.

Gorenstein, P. 1981. In Proc. 17th Cosmic Ray Conf. (Paris) 12: 99.

Gorenstein, P., and Tucker, W. H. 1976. Ann. Rev. Astron. Astrophys. 14: 373.

Haisch, B. M. 1983. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 255. Dordrecht: Reidel.

Haisch, B. M., Linsky, J., Harnden, Jr., F. R., Rosner, R., Seward, F., and Vaiana, G. S. 1980. Ap. J. Lett. 242: L99.

Hall, D. S. 1976. In Multiple Periodic Variable Stars. W. S. Fitch, editor, p. 287. Dordrecht: Reidel.

Hammer, R. 1983. Adv. Space Res. 2(9): 261.

Harnden, Jr., F. R., Branduardi, G., Elvis, M., Gorenstein, P., Grindlay, J. E. et al. 1979. Ap. J. Lett. 234: L51.

Hartmann, L. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects, J. Stenflo, editor, p. 419. Dordrecht: Reidel.

Hartmann, L., and MacGregor, K. B. 1980. Ap. J. 242: 260.

Hartmann, L., Baliunas, S. L., Duncan, D. K., and Noyes, R. W. 1984. Ap. J. 279: 778.

Helfand, D. J., and Caillault, J.-P. 1982. Ap. J. 253: 766.

Hearn, A. G. 1972. Astron. Astrophys. 19: 417.

Hearn, A. G. 1975. Astron. Astrophys. 40: 355.

Hearn, A. G. 1984. In The Origins of Non-Radiative Energy and Momentum in Hot Stars. A. B. Underhill, editor.

Holt, S. S., White, N. E., Becker, R. H., Boldt, E. A., Mushotzky, R. F. et al. 1979. Ap. J. Lett. 234: L65.

Holzer, T. E., Fla, T., and Leer, E. 1983. Ap. J. 275: 808.

Howard, R., and LaBonte, B. J. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 101. Dordrecht: Reidel.

Ionson, J. A. 1978. Ap. J. 226: 650.

Ionson, J. A. 1982. Ap. J. 254: 318.

Johnson, H. M. 1981. Ap. J. 243: 234.

Johnson, H. M. 1983a. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 109. Dordrecht: Reidel.

Johnson, H. M. 1983b. Ap. J. 273: 702.

Jordan, C. 1976. Phil. Trans. R. Soc. London Ser. A 281: 391.

Kahler, S., Golub, L., Harnden, Jr., F. R., Liller, W., Seward, F., et al. 1982. Ap. J. 252: 239.

Kahn, F. D. 1981. M.N.R.A.S. 196: 641.

Kraft, R. P. 1967. Ap. J. 150: 551.

Krolik, J. H., and Kallman, T. R. 1983. Ap. J. 267: 610.

Ku, W. H.-M., Righini-Cohen, G., and Simon, M. 1982. Science 215: 61.

Ku, W. H.-M., and Chanan, G. A. 1979. Ap. J. Lett. 234: L59.

Kunkel, W. E. 1969. Nature 222: 1129.

Kuperus, M., Ionson, J. A., and Spicer, D. S. 1981. Ann. Rev. Astron. Astrophys. 19: 7.

Landini, M., and Monsignori-Fossi, B. C. 1975. Astron. Astrophys. 42: 213.

Landini, M., Monsignori-Fossi. B. C., and Pallavicini, R. 1984a. In Proc. 8th Int. Colloquium on EUV and X-ray Spectroscopy of Astrophys. and Laboratory Plasmas, Washington, D.C. (August 1984).

Landini, M., Monsignori-Fossi, B. C., Paresce, F., and Stern, R. 1984b. Ap. J. (submitted).

Leer, E., Holzer, T. E., and Fla, T. 1982. Space Sci. Rev. 33: 161.

Lepp, S., and McCray, R. 1983. Ap. J. 269: 560.

Lin, R., Schwartz, R. A., Kane, S. R., Pelling, R. M., and Hurley, K. C. 1984. Ap. J. 283: 421.

Linsky, J. L. 1981a. In Solar Phenomena in Stars and Stellar Systems, R. M. Bonnet and A. K. Dupree, editors, p. 99. Dordrecht: Reidel.

Linsky, J. L. 1981b. In X-ray Astronomy In The 1980's. S. S. Holt, editor, p. 13, NASA TM-83848.

Linsky, J. L. 1982. In Advances in Ultraviolet Astronomy: Four Years of IUE Research, p. 17. NASA CP-2238.

Linsky, J. L. 1983a. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 313. Dordrecht: Reidel.

Linsky, J. L. 1983b. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 39. Dordrecht: Reidel.

Linsky, J. L. 1984. In Cool Stars, Stellar Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 244. New York: Springer.

Linsky, J. L., and Haisch, B. M. 1979. Ap J. Lett. 229: L27.

Long, K., and White, R. L. 1980. Ap. J. Lett. 239: L65.

Lucy, L. B. 1982. Ap. J. 255: 286.

Lucy, L. B., and Solomon, P. M. 1970. Ap. J. 159: 879.

Lucy, L. B., and White, R. L. 1980. Ap. J. 241: 300.

Maccacaro, T., Avni, Y., Gioia, I. M., Giommi, P., Griffiths, R. E., et al. 1982. Ap. J. 253: 504.

MacGregor, K. B. 1983. In Solar Wind V, M. Neugebauer, editor, p. 241. NASA CP-2280.

MacGregor, K. B., Hartmann, L., and Raymond, J. C. 1979. Ap. J. 231: 514.

Maggio, A., Bookbinder, J., Harnden, Jr., F. R., Golub, L., Majer, P., et al. 1984. In Symp. X-ray Astronomy 84, Bologna, Italy, in press.

Majer, P., Schmitt, J. H. M. M., Golub, L., Harnden, F. R. Jr., and Rosner, R. 1984. BAAS 16: 514.

Mangenay, A., and Praderie, F. 1984. Astron. Astrophys. 130: 143.

Marcy, G. W. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 3. Dordrecht: Reidel.

Marilli, E., and Catalano, S. 1984. Astron. Astrophys. 133: 57.

Martens, P. C. H. 1979. Astron. Astrophys. Lett. 75: L7.

Maxson, C. W., and Vaiana, G. S. 1977. Ap. J. 215: 919.

McIntosh, P. S., Krieger, A. S., Nolte, J. T., and Vaiana, G. S. 1976. Solar Phys. 49: 57.

Mewe, R. 1979. Space Sci. Rev. 24: 101.

Mewe, R. 1984. In Proc. 8th Int. Colloquium on EUV and X-ray Spectroscopy of Astrophys. and Laboratory Plasmas, Washington, D.C. (August 1984).

Mewe, R., Heise, J., Gronenschild, E. H. B. M., Brinkman, A. C., Schrijver, C. J., and Den Boggende, A. J. F. 1975. Ap. J. Lett. 202: L67.

Mewe, R., Schrijver, C. J., and Zwaan, C. 1981. Space Sci. Rev. 30: 191.

Mewe, R., Gronenschild, E. H. B. M., Westergaard, N. J., Heise, J., Seward, F. D. et al. 1982. Ap. J. 260: 233.

Mewe, R., and Zwaan, C. 1980. In Cool Stars, Stellar Systems, and the Sun. A. K. Dupree, editor, p. 123. SAO Report No. 389.

Meyer, J. P. 1981. In Proc. 17th Int. Cosmic Ray Conf. (Paris) 12: 265.

Meyer, J. P. 1985. Ap. J. Suppl., in press.

Micela, G., Sciortino, S., and Serio, S. 1984. In Symp. X-ray Astronomy 84, Bologna, Italy, in press.

Micela, G., Sciortino, S., Serio, S. Vaiana, G. S., Golub, L. et al. 1985. Ap. J., in press.

Montmerle, T. 1984. In Proc. XXV COSPAR Symp. on Particle Acceleration Phenomena, Nucleosynthesis and Cosmic Rays, Graz, Austria (June 25-30,

1984).

Montmerle, T., Koch-Miramond, L., Falgarone, E., and Grindlay, J. 1983. Ap. J. 269: 182.

Mullen, D. J. 1979. Ap. J. 234: 588.

Mullen, D. J. 1983. In Activity in Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 527. Dordrecht: Reidel.

Mundt, R. 1981. Astron. Astrophys. 95: 234.

Nelson, G. D., and Hearn, A. G. 1978. Astron. Astrophys. 65: 223.

Nordlund, A. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 79. Dordrecht: Reidel.

Noyes, R. W. 1981. In Solar Phenomena in Stars and Stellar Systems. R. M. Bonnet and A. K. Dupree, editors. Dordrecht: Reidel.

Noyes, R. W. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 133. Dordrecht: Reidel.

Noyes, R. W., Hartmann, L., Baliunas, S., Duncan, D., and Vaughan, A. H. 1984. Ap. J. 279: 763.

Nugent, J., and Garmire, G. 1978. Ap. J. Lett. 226: L38.

Orrall, F. Q. 1981. Solar Active Regions, editor. Boulder: Colorado Associated Univ. Press.

Oskanyan, V. S., Evans, D. S., Lacy, C., and McMillan, R. S. 1977. Ap. J. 214: 430.

Osterbrock, D. E. 1961. Ap. J. 134: 347.

Owocki, S. P., and Rybicki, G. B. 1984. Ap. J. 284: 337.

Pallavicini, R. P., Peres, G., Serio, S., Vaiana, G. S., Golub, L., and Rosner, R. 1981. Ap. J. 247: 692.

Pallavicini, R. P., Golub, L., Rosner, R., and Vaiana, G. S., Ayres, T., and Linsky, J. L. 1981. Ap. J. 248: 279.

Pallavicini, R. P., Golub, L., Rosner, R., and Vaiana, G. S. 1982. In Cool Stars, Stellar Systems, and the Sun (Vol. II). M. S. Giampapa and L. Golub, editors, p. 77. Washington, D.C.: Smithsonian SP-392.

Parker, E. N. 1955. Ap. J. 122: 293.

Parker, E. N. 1975. Ap. J. 198: 205.

Parker, E. N. 1979. Cosmical Magnetic Fields. Oxford: Clarendon Press.

Parker, E. N. 1983a. Ap. J. 264: 635.

Parker, E. N. 1983a. Ap. J. 264: 642.

Patterson, J. 1984. Ap. J. Suppl. 54: 443.

Priest, E. R. 1981. In Solar Active Regions. F. Q. Orrall, editor. Boulder:

Colorado Associated Univ. Press.

Priest, E. R. 1983. Solar Magnetohydrodynamics

Rappaport, S., Verbunt, F., and Joss, P. C. 1983. Ap. J. 275: 713.

Raymond, J. C., and Smith, B. W. 1977. Ap. J. Suppl. 35: 419.

Rengarajan, T. N. 1984. Ap. J. Lett. 283: L63.

Rengarajan, T. N., and Verma, R. P. 1983. M.N.R.A.S. 203: 1035.

Robinson, R. D., Worden, S. P., and Harvey, J. 1980. Ap. J. 239: 961.

Rosner, R. 1980. In Cool Stars, Stellar Systems, and the Sun. A. K. Dupree, editor, p. 79. SAO Report No. 389.

Rosner, R. 1983a. Adv. Space Res. 2(9): 3.

Rosner, R. 1983b. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 279. Dordrecht: Reidel.

Rosner, R., Tucker, W. H., and Vaiana, G. S. 1978. Ap. J. 220: 643.

Rosner, R., Golub, L., Coppi, B., and Vaiana, G. S. 1978. Ap. J. 222: 317.

Rosner, R., and Vaiana, G. S. 1980. In X-ray Astronomy, R. Giacconi and G. Setti, editors. Dordrecht: Reidel.

Rosner, R., Avni, Y., Bookbinder, J., Giacconi, R., Golub, L. et al. 1981. Ap. J. Lett. 249: L5.

Rosner, R., Golub, L., and Vaiana, G. S. 1985. Ap. J., in press.

Roxburgh, I. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 449. Dordrecht: Reidel.

Rucinski, S. M. 1984. Astron. Astrophys. Lett. 132: L9.

Schmitt, J. H. M. M. 1984a. In X-ray Astronomy 84, Symposium, Bologna (in press).

Schmitt, J. H. M. M. 1984b. Ap. J., in press.

Schmitt, J. H. M. M., and Rosner, R. 1983. Ap. J. 265: 901.

Schmitt, J. H. M. M., and Rosner, R. 1985. JASA (submitted).

Schmitt, J. H. M. M., Rosner, R., and Bohn, U. H. 1984. Ap. J. 282: 316.

Schmitt, J. H. M. M., Harnden, Jr., F. R., Peres, G., Rosner, R., and Serio, S. 1984. Ap. J., in press.

Schmitt, J. H. M. M., Golub, L., Harnden, Jr., F. R., and Rosner, R. 1985. Ap. J., in press.

Schrijver, C. J. 1982. Thesis, Univ. of Utrecht.

Schrijver, C. J. 1983. Astron. Astrophys. 127: 289.

Schrijver, C. J., Mewe, R., and Walter, F. M. 1984a. Astron. Astrophys. 138: 258.

Schrijver, C. J., Mewe, R., and Walter, F. M. 1984b. In Cool Stars, Stellar

Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 166. New York: Springer.

Schrijver, C. J., Mewe, R., and Zwaan, C. 1983. Adv. Space Res. 2(9): 243.

Schussler, M. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 213. Dordrecht: Reidel.

Schwartz, R. D. 1978. Ap. J. 223: 884.

Schwarzschild, M. 1948. Ap. J. 107: 1.

Serio, S. 1983. Adv. Space Res. 2(9): 271.

Serio, S. 1984. In X-ray Astronomy 84, Symposium, Bologna (Italy).

Serio, S., Peres, G., Vaiana, G. S., Golub, L., and Rosner, R. 1981. Ap. J. 243: 288.

Seward, F. D., Forman, W. R., Giacconi, R., Griffiths, R. E., Harnden, Jr., F. R., Jones, C., and Pye, J. P. 1979. Ap. J. Lett. 234: L55.

Sekiya, M., Hayashi, C., and Nakazawa, K. 1981. Prog. Theor. Phys. 66: 1301.

Shu, F. H., and Terebey, S. 1984. In Cool Stars, Stellar Systems, and the Sun, S. Baliunas and L. Hartmann, editors, p. 78. New York: Springer Verlag.

Silk, J., and Norman, C. 1983. Ap. J. Lett. 272: L49.

Simon, T., Linsky, J. L., and Stencel, R. E. 1982. Ap. J. 257: 225.

Skumanich, A. 1972, Ap. J. 171: 565.

Skumanich, A., Lean, J. L., White, O. R., and Livingston, W. C. 1984. Ap. J. 282: 776.

Smith, M. A., Pravdo, S. H., and Ku, W. H.-M. 1983. Ap. J. 272: 163.

Soderblom, D. R. 1983. Ap. J. Suppl. 53: 1.

Soderblom, D. R. 1984. In Cool Stars, Stellar Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 205. New York: Springer.

Spiegel, E. A., and Weiss, N. O. 1980. Nature 287: 616.

Spiegel, E. A., and Weiss, N. O. 1981. Columbia Univ. Preprint No. A10.

Spruit, H. C. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 41. Dordrecht: Reidel.

Spruit, H. C., and Ritter, H. 1983. Astron. Astrophys. 124: 267.

Stauffer, J. R., Hartmann, L., Soderblom, D. R., and Burnham, N. 1984. Ap. J. 280: 202.

Stern, R. A. 1983. Adv. Space Sci., 2: 39.

Stern, R. A. 1984. In Cool Stars, Stellar Systems, and the Sun. S. Baliunas and L. Hartmann, editors, p. 150. New York: Springer.

Stern, R. A., Underwood, J. H., and Antiochos, S. K. 1983. Ap. J. Lett. 264: L55.

Stern, R. A., Zolcinski, M. C., Antiochos, S. K., and Underwood, J. H. 1981. Ap. J. 249: 647.

Stocke, J. T., Liebert, J., Gioia, I. M., Griffiths, R. E., Maccacaro, T. et al. 1983. Ap. J. 273: 458.

Sturrock, P. A. 1980. Skylab Solar Flare Workshop Proceedings, editor. Boulder: Colorado Associated Univ. Press.

Sturrock, P. A., and Uchida, Y. 1981. Ap. J. 246: 331.

Stenflo, J. 1983. Editor, Solar and Stellar Magnetic Fields: Origins and Coronal Effects. Dordrecht: Reidel.

Swank, J. H., and Johnson, H. M. 1982. Ap. J. Lett. 259: L67.

Swank, J. H., White, N. E., Holt, S. S., and Becker, R. H. 1981. Ap. J. 246: 208.

Tassoul, M., and Tassoul, J.-L. 1984. Ap. J. 286: 350.

Topka, K., Avni, Y., Golub, L., Gorenstein, P., Harnden, Jr., F. R., Rosner, R., and Vaiana, G. S. 1982. Ap. J. 259: 677.

Tucker, W. H. 1973. Ap. J. 187: 285.

Uchida, Y. 1984. In The Origins of Non-Radiative Energy and Momentum in Hot Stars. A. B. Underhill, editor.

Uchida, Y., and Sakurai, T. 1983. In Activity of Red Dwarf Stars. P. B. Byrne and M. Rodono, editors, p. 629. Dordrecht: Reidel.

Ulmschneider, P. 1979. Space Sci. Rev. 24: 71.

Ulrich, R. K. 1976. Ap. J. 210: 377.

Underhill, A. B. 1984. Editor, The Origin of Non-Radiative Energy and Momentum in Hot Stars. NASA CP.

Vaiana, G. S. 1981a. Space Sci. Rev. 30: 151.'

Vaiana, G. S. 1981b. Inst. Space Astronaut. Sci. (Tokyo), Report No. 597.

Vaiana, G. S. 1982. X-ray Astronomy In The 1980's, S. S. Holt, editor. NASA TM-83848.

Vaiana, G. S. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 165. Dordrecht: Reidel.

Vaiana, G. S., et al. 1981. Ap. J. 245: 163.

Vaiana, G. S., et al. 1982. In Cool Stars, Stellar Systems, and the Sun. M. S. Giampapa and L. Golub, editors. Washington, D.C.: Smithsonian SP-392.

Vaiana, G. S., Krieger, A. S., and Timothy, A. F. 1973. Solar Phys. 32: 81.

Vaiana, G. S., Krieger, A. S., and Van Speybroeck, L. P. 1970. in IAU Symposium No. 42.

Vaiana, G. S., and Rosner, R. 1978. Ann. Rev. Astron. Astrophys. 16: 393.

Van Buren, D. 1984. Ap. J., submitted.

Van Speybroeck, L. P., Krieger, A. S., and Vaiana, G. S. 1970. Nature 227: 818.

Vaughan, A. H. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 113. Dordrecht: Reidel.

Vaughan, A. H. 1984. Science 225: 793.

Vaughan, A. H., et al. 1981. Ap. J. 250: 276.

Vedder, P. W., and Canizares, C. R. 1983. Ap. J. 270: 666.

Verbunt, F., and Zwaan, C. 1981. Astron. Astrophys. 100: L7.

Vesecky, J. F., Antiochos, S. K., and Underwood, J. H. 1979. Ap. J. 233: 987.

Waldron, W. L. 1984. Ap. J. 282: 256.

Walter, F. W. 1981. Ap. J. 245: 677.

Walter, F. W. 1982. Ap. J. 253: 745.

Walter, F. W., and Bowyer, S. 1981. Ap. J. 245: 671.

Walter, F. W., Cash, W., Charles, P. A., and Bowyer, C. S. 1980. Ap. J. 236: 212.

Walter, F. M., Gibson, D. M., and Basri, G. S. 1983. Ap. J. 267: 665.

Walter, F. M., and Kuhi, L. V. 1981. Ap. J. 250: 254.

Walter, F. W., Linsky, J. L., Simon, T., Golub, L., and Vaiana, G. S. 1984. Ap. J. 281: 815.

Wentzel, D. G. 1978. Rev. Geophys. Space Phys. 16: 757.

Westergaard, N. J., Hansen, L., Jorgensen, H. E., Norgaard-Nielsen, H. U., Rasmussen, I. L., and Schnopper, H. W. 1985. In Adv. in Space Res. (Proc. COSPAR, Graz, Austria, June 1984) (in press).

White, N. E., and Marshall, F. E. 1983. Ap. J. Lett. 269: L117.

White, N. E., Culhane, J. L., Parmar, A. N., Kellett, B., Kahn, S., van den Oort, G. H. J., and Kuijpers, J. 1984. In 18th ESLAB Symposium on X-ray Astronomy (Scheveningen, The Hague, The Netherlands).

White, R. L. 1985. Ap. J., in press (15 Feb.).

White, R. L., and Becker, R. H. 1983. Ap. J. 272: L19.

Willson, R. C., Gulkis, S., Janssen, M., Hudson, H. S., and Chapman, G. A. 1981. Science 211: 700.

Wilson, O. C. 1966. Ap. J. 144: 695.

Wilson, O. C. 1978. Ap. J. 226: 379.

Withbroe, G. L. 1975. Solar Phys. 45: 301.

Withbroe, G. L. 1981. In Solar Active Regions. F. Q. Orrall, editor, p. 199. Boulder: Colorado Associated Univ. Press.

Withbroe, G. L., and Noyes, R. W. 1977. Ann. Rev. Astron. Astrophys. 15: 363.

Wragg, M. A., Priest, E. R. 1981. Solar Phys. 70: 293.

Young, A., and Koniges, A. 1977. Ap. J. 211: 836.

Zahnle, K. J., and Walker, J. 1982. Rev. Geophys. Space Phys. 20: 280.

Zirker, J. 1977. Editor. Solar Coronal Holes. Boulder: Colorado Associated Univ. Press.

Zirin, H. 1975. Ap. J. Lett. 199: L163.

Zirin, H. 1982. Ap. J. 260: 655.

Zolcinski, M. C., Antiochos, S. K., Walker, A. B. C., and Stern R. A. 1982. Ap. J. 258: 177.

Zombeck, M. Z., Vaiana, G. S., Haggerty, R., Krieger, A. S., Silk, J. K., and Timothy, A. F. 1979. Ap. J. Suppl. 38: 69.

Zwaan, C. 1980. In The Sun as a Star. S. Jordan, editor, p. 163. NASA SP-450.

Zwaan, C. 1983. In Solar and Stellar Magnetic Fields: Origins and Coronal Effects. J. Stenflo, editor, p. 85. Dordrecht: Reidel.

FIGURE CAPTIONS

Figure 1: Schematized indication of where stellar x-ray emission has been detected in the Hertzsprung-Russell diagram.

Figure 2: Integral x-ray luminosity functions for F, G, and M stars on the main sequence, as derived from volume-limited samples observed by the Einstein Observatory (Rosner et al. 1981; Bookbinder, Golub, Schmitt, and Rosner 1984; Maggio et al. 1984; Majer et al. 1984; Schmitt et al. 1984); the Sun's coronal luminosity places it near the bottom of this distribution of stars in this spectral type range.

Figure 3: Scatter diagram of soft x-ray luminosity versus rotation rate, adapted from Pallavicini et al. (1981, 1982), and further updated using both newly-analyzed Einstein data as well as recent EXOSAT data (courtesy J. Schmitt). Only stars with either measured or bounded rotation rates are shown. Note that in spite of the diversity of stellar types in this sample, the correlation between x-ray luminosity and rotation period remains very strong.

Figure 4: Cumulative x-ray luminosity functions for G stars in the Pleiades and Hyades open clusters, and for dwarf G field stars; note the clear age effect -- the cumulative x-ray luminosity function shows a systematic shift to lower emission levels as the stars age.

Figure 5: X-ray emission at the red end of the main sequence: (a) scatter diagram for the variation of x-ray luminosity with spectral type in the interval M0-M8; (b) comparison of the derived cumulative x-ray luminosity functions for M stars < M5 and > M5. See text for discussion.

Figure 6: In this figure, we plot (solid curve) the log of the predicted number of stars observed per square degree whose x-ray flux lies above a threshold value S, log N(>S), versus the log of this threshold flux, as derived for stars in the spectral type range M0-M5 from the pointed Einstein Observatory stellar data (i.e., using the luminosity function

shown in Figure 6, and the M dwarf spatial distribution in our galaxy from the model of Bahcall and Soneira 1980). Also shown are (a) the observed values of log N(>S)-log S for all stars derived from the Einstein Observatory Medium Sensitivity Survey (Maccacaro et al. 1982; Stocke et al. 1983), and (b) the log N(>S)-log S curves (dashed curves) for stars in the spectral type range M5-M8 under two distinct assumptions: (i) their x-ray luminosity function is identical to that of the earlier spectral type, and (ii) the observed sample is a fair representative of the universe of such M dwarf stars (so that the x-ray luminosity function derived directly from the data is used). Note that the stars in the range M0-M5 already satisfy the observed x-ray log N-log S behavior, so that the stars in the range M5-M8 cannot possibly be vigorous x-ray emitters. The results shown here are taken from Bookbinder et al. (1984).

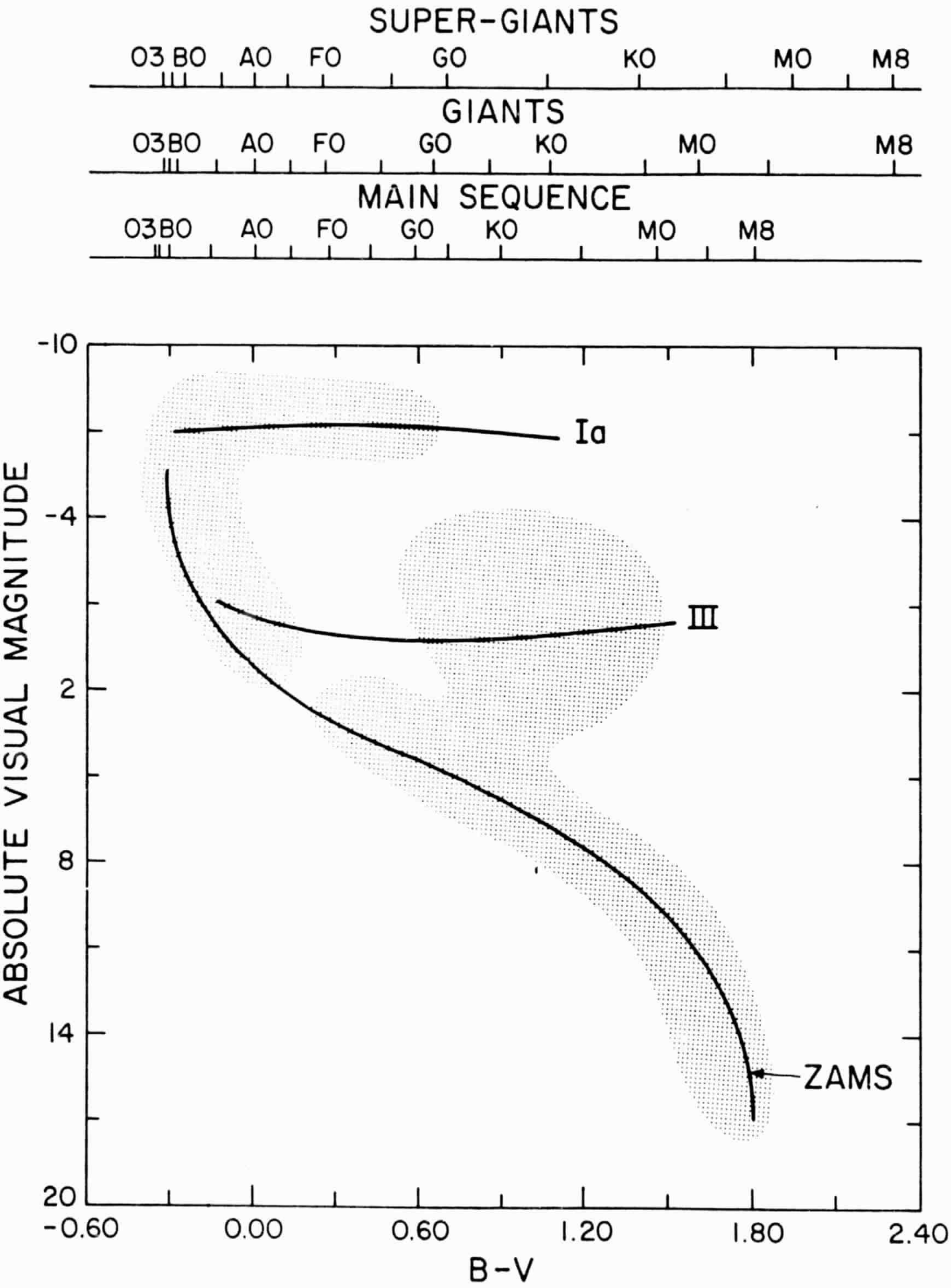
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Figure 1

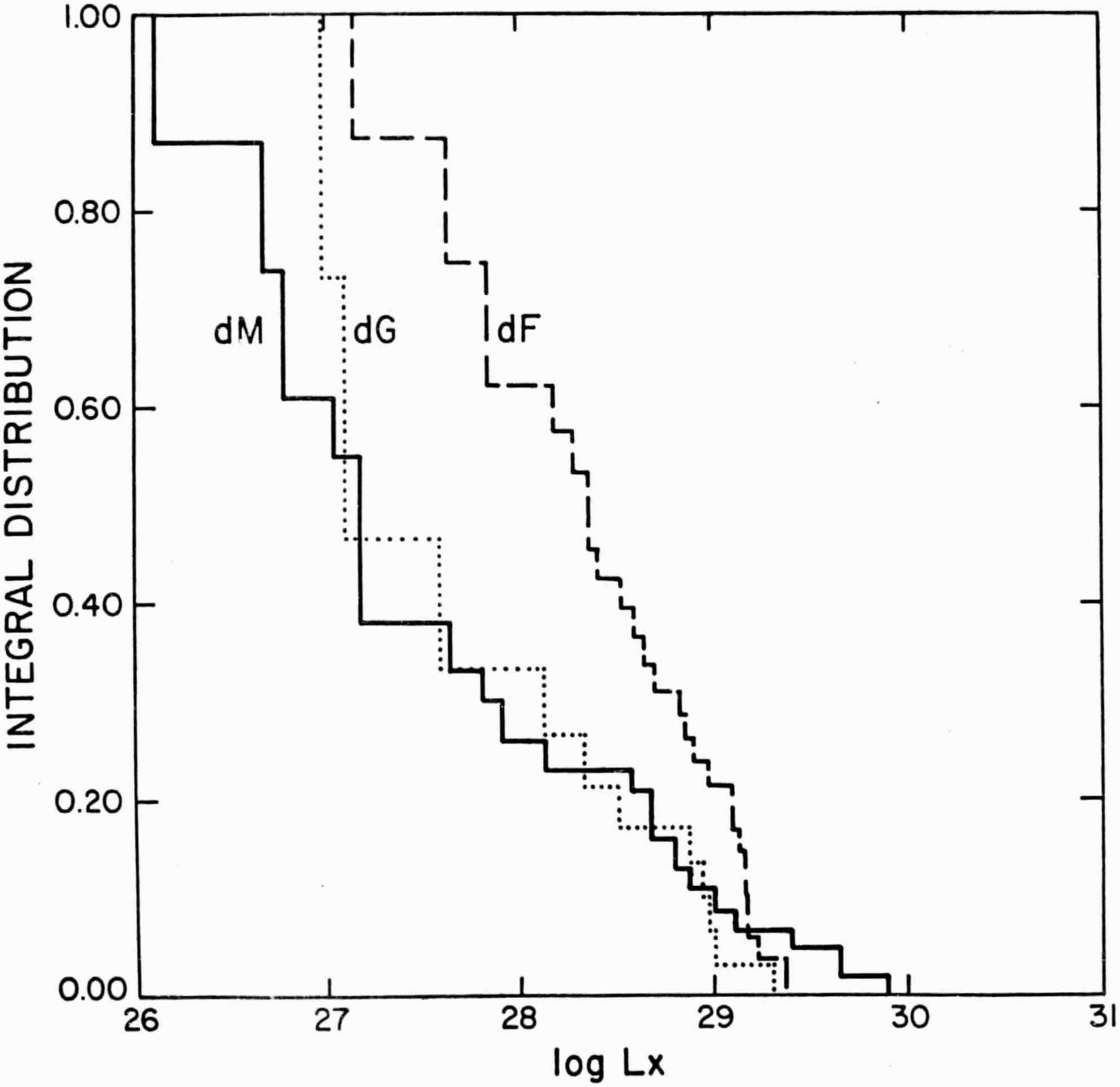

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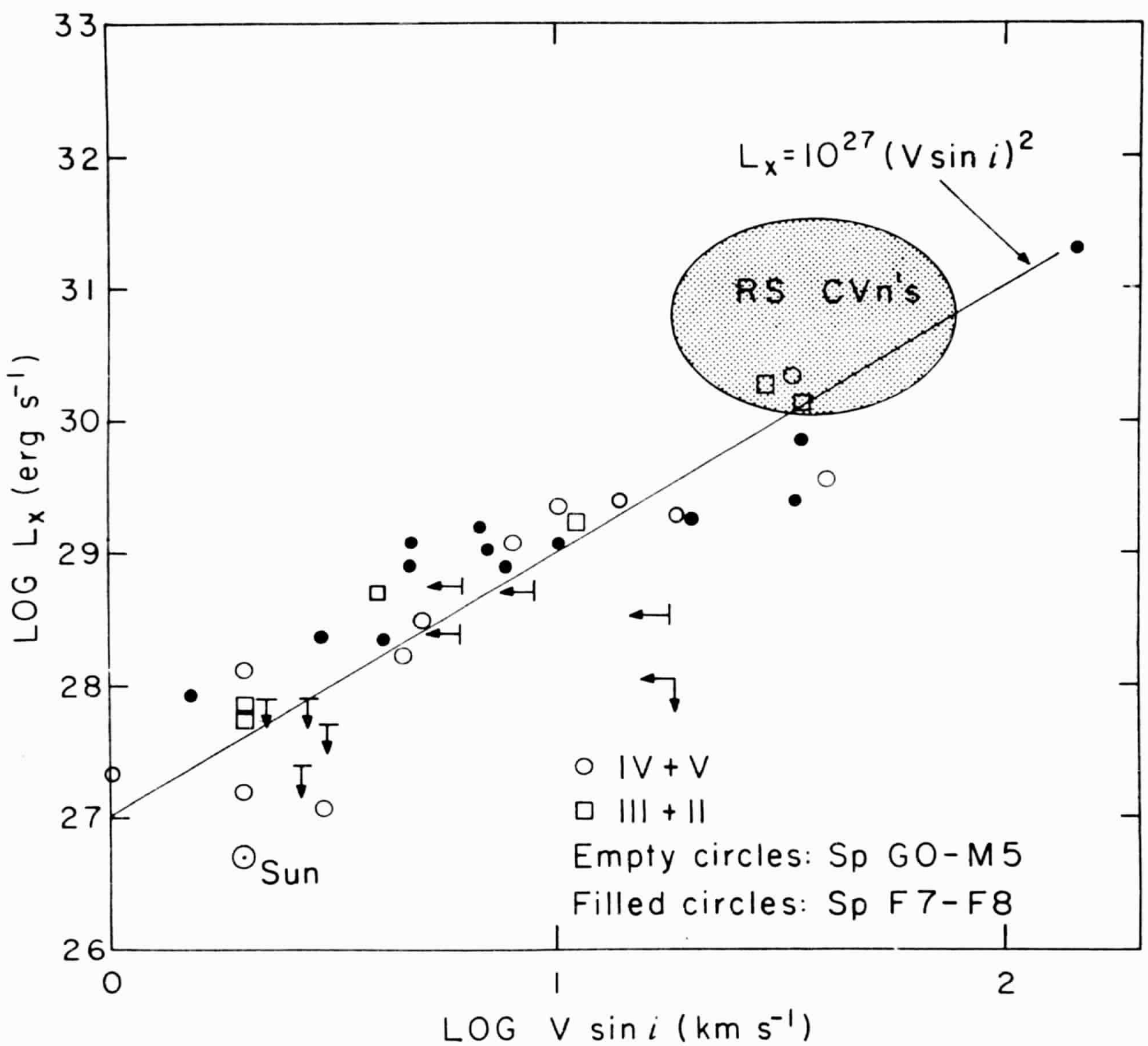
Figure 2



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LOG L_x (erg s^{-1})
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LOG V sin i (km s^{-1})
$L_x = 10^{27} (V \sin i)^2$
RS CVn's
Sun
○ IV + V
□ III + II
Empty circles: Sp GO-M5
Filled circles: Sp F7-F8

Figure 3

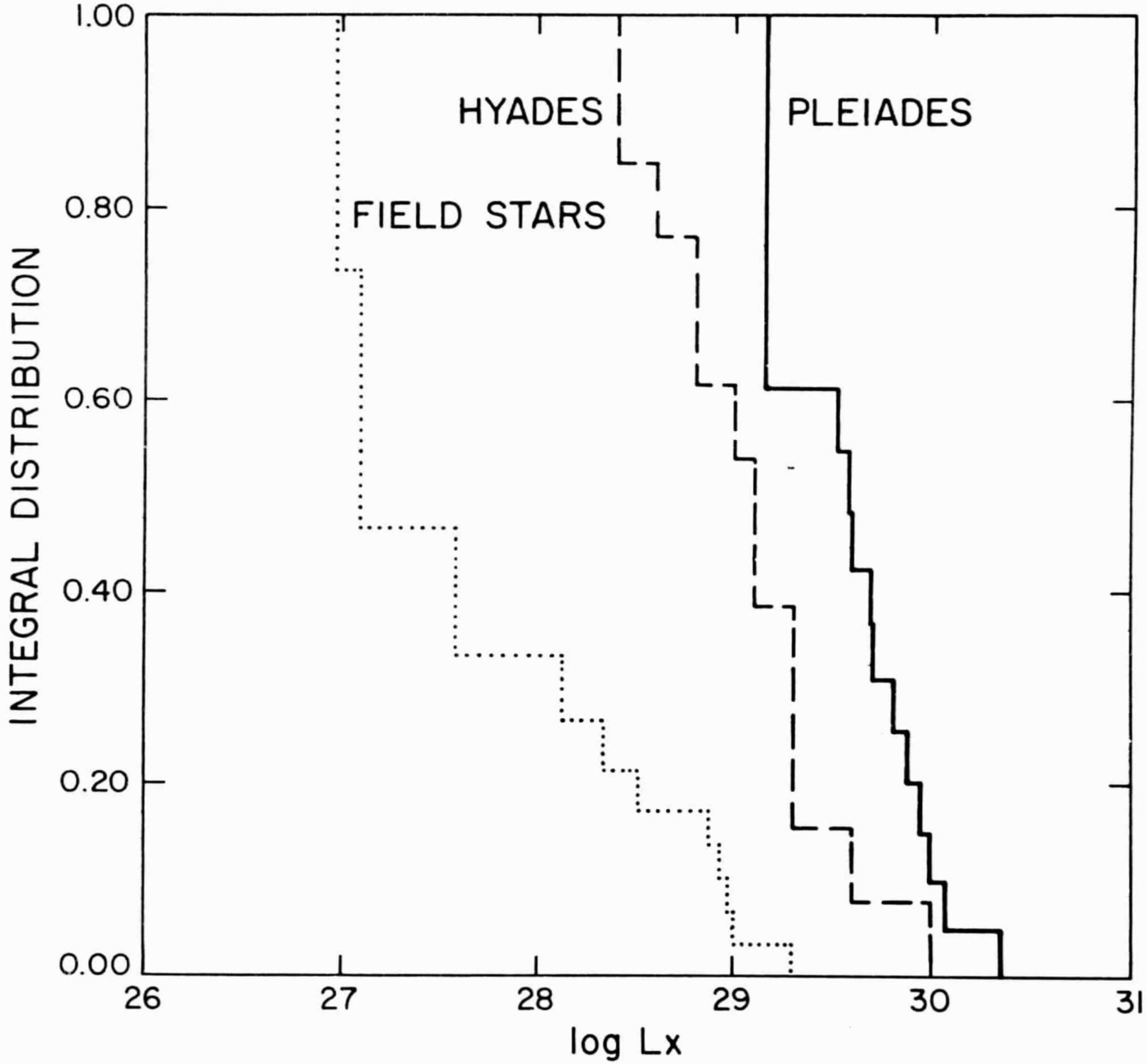
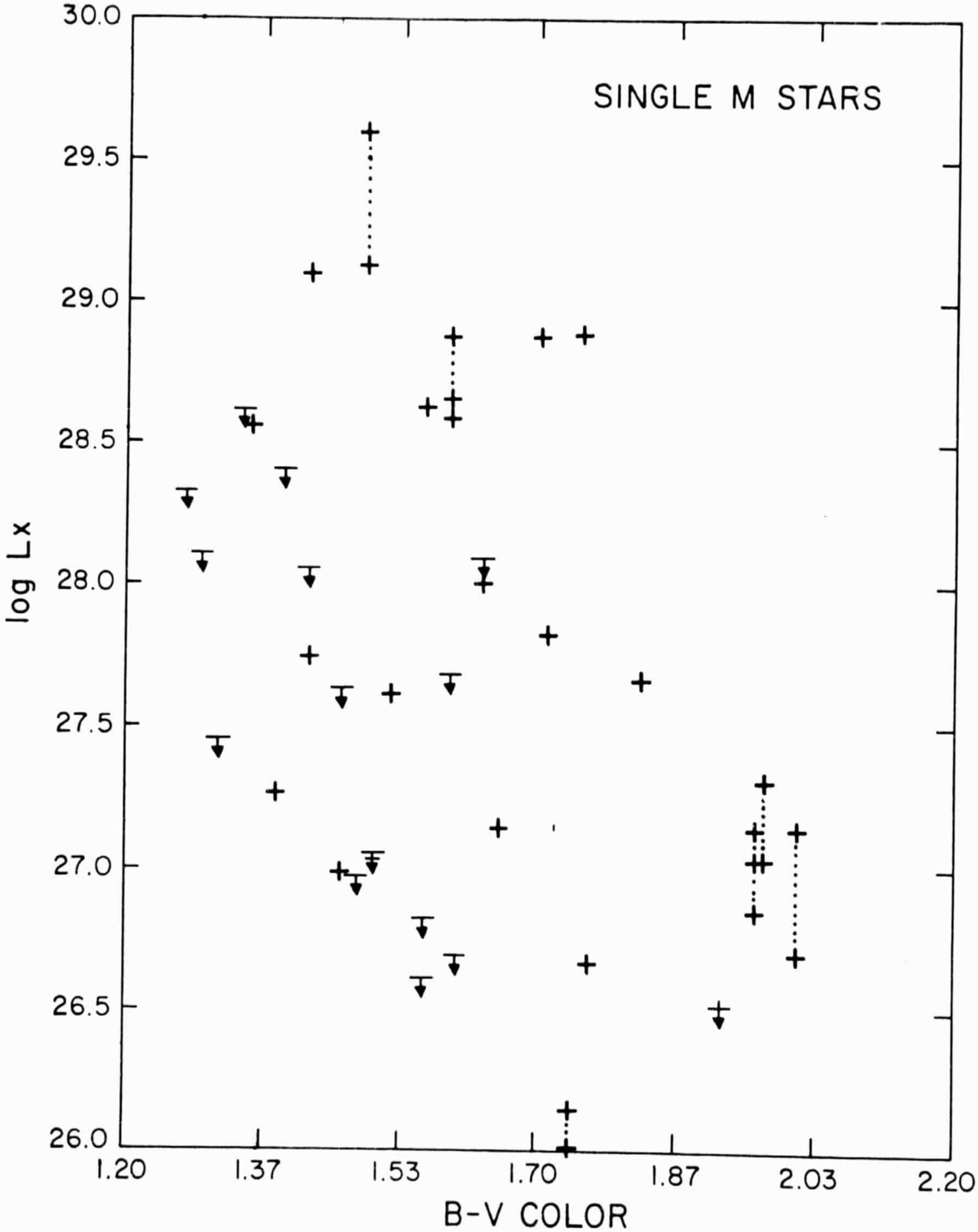
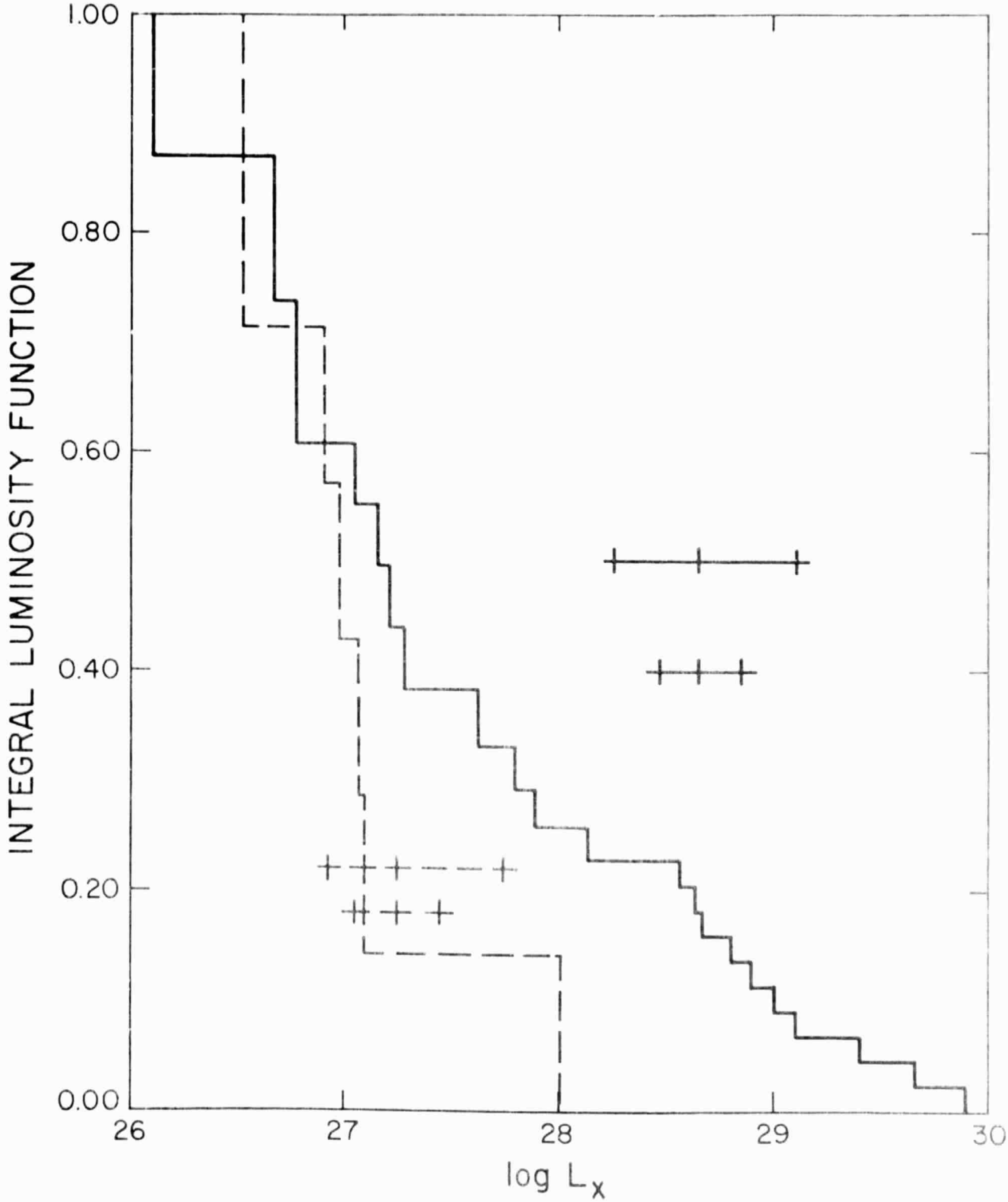

1.00
0.80
0.60
0.40
0.20
0.00
INTEGRAL DISTRIBUTION
26
27
28
29
30
31
log Lx
HYADES
PLEIADES
FIELD STARS

Figure 4



SINGLE M STARS
log Lx
B-V COLOR
30.0
29.5
29.0
28.5
28.0
27.5
27.0
26.5
26.0
1.20
1.37
1.53
1.70
1.87
2.03
2.20

Figure 5a



INTEGRAL LUMINOSITY FUNCTION
1.00
0.80
0.60
0.40
0.20
0.00
26
27
28
29
30
log L_x

Figure 5b

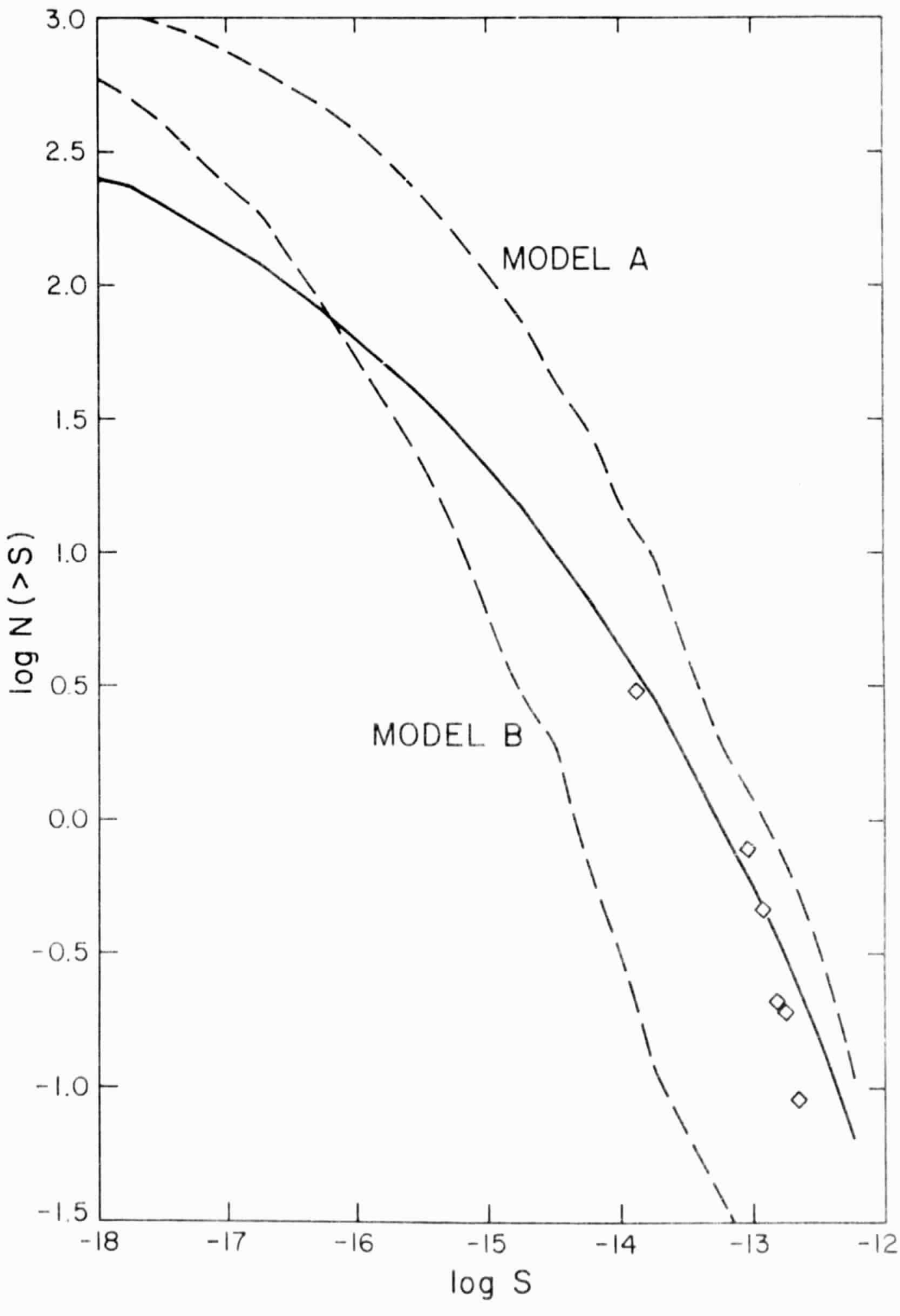

3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
log N (>S)
MODEL A
MODEL B
-18
-17
-16
-15
-14
-13
-12
log S

Figure 6

The Time Resolution Domain of Stellar Radio Astronomy

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I. Introduction

While the origins of stellar radio astronomy have their roots in time-variable phenomena, high time resolution (HTR) radio observations of stellar sources is a very young technique. This is a somewhat surprising development in light of the historical origin of stellar radio astronomy, which was exclusively concerned with the flare activity associated with dMe stars. One would expect that, having detected the flare emission, higher time resolution would have been employed to elucidate the time structure of the flare, thereby providing constraints on the emission and particle acceleration mechanisms. Rather, focus shifted from flare observations to detecting a variety of stellar sources at ever-lower flux levels, so that "quiescent" emission has been detected from several areas on the HR diagram. In fact, we shall see below that it may be possible that high time resolution studies can clarify the nature of the "quiescent" emission in some stellar sources.

A number of basic questions are appropriate for discussion at this point. What constitutes high time resolution in the context of stellar radio observations? For what sources are these observations likely to yield interesting results? And what current problems in understanding the emission can best be addressed by these observations? Can we use the solar analogue, and in particular the concept of the "solar-stellar connection", as a guide for our observations? Is it possible for these observations to provide us with a better understanding of related stellar properties, i.e. such as the nature of the stellar dynamo? Finally, are the facilities that are currently available or will be available in the near future suitable for making these observations?

For the purposes of our discussion, high time resolution refers to timescales that are short compared to either the hydrodynamic flow timescale or the thermal cooling timescale. We are thus selecting emission processes that are typically called "non-thermal", even if the underlying electron distribution is "thermal", i.e. Maxwellian. With this criteria, we eliminate from our discussion the free-free bremmstrahlung emission from, e.g., most O stars, which are variable, for example, on the timescales of months (see however, Abbott, Bieging and Churchwell 1984 and White 1984).

One consequence of higher time resolution is a better estimate for the brightness temperature, T_B, that is determined for the source. In general, one assumes that the timescale of variability represents some real propagation effect of the exciting phenomenon, and thus a characteristic velocity. This yields an upper limit on the true source size, which is simply related to the brightness

temperature by:

$$T_B = 6.41 \times 10^{10} (S_f/f^2) (d/R)^2$$

where S_f is the radio flux at frequency f, d is the distance to the star in pc and R is the source size in. units of solar radii. Obviously, low time resolution observations only provide a lower limit on the source's true brightness temperature. If R_s is to be reasonably constrained for most stellar flare observations (using the rise-time of the flare), then the integration times must not exceed about one second for M dwarfs. A second effect of long integration times is to reduce the peak fluxes by averaging the instantaneous fluxes over the integration time. One example of this effect is found in the observations of Gary, Linsky and Dulk (1982) of a flare on L726-A (one of the components of UV Ceti). Their five minutes integrations gave a peak flux of under 12 mJy, while 10 second integrations had peak fluxes over 17 mJy and showed evidence that finer, but unresolved, time structure existed. The importance of a strong constraint on T_B cannot be over-emphasized in terms of limiting the possible emission mechanisms: if $T_B > 3 \times 10^8$, the emission is probably coherent; if $T_B > 10^{12}$, then there are no possible incoherent emission mechanisms. By coincidence, these short timescales are also near the observational limits imposed by the current generation of radio telescopes. In general, observations on longer timescales have few instrumental restrictions since long integration times do not hamper variability studies on those timescales.

Given the above restrictions on the emission mechanisms and timescales, what stellar sources lend themselves to HTR observations? Besides the sun, Gibson (1984) has compiled a list of 77 stellar sources that show evidence of "non-thermal" emission. Among these, nine are listed as sources of coherent radiation, and another nine have been observed with both coherent and incoherent emission. Each of these sources is therefore a good candidate for HTR observations. These sources cover a wide range of the HR diagram, with some significant gaps, but are mostly M giants, flare stars (M dwarfs), RS CVn systems and Wolf-Rayet and O stars and Algol-type binaries. We will restrict our discussion to the late-type stars and to the RS CVn systems, even though many of the points made in the following discussion are valid for the more exotic sources such as SS433, Cyg X-3 and Cir X-1. We will discuss as examples some of these sources and identify what information HTR observations can provide.

II. Solar-type Stars

Flare stars have been the object of radio variability studies for over twenty years, since Lovell (1963) first observed stellar flares. Since then, observations have been made from below 20 Mhz to about 15 Ghz, with a variety of sensitivities and time resolutions. For these stars in particular, the use of the solar analogy may be quite apt, given that the overall structure of the stars is quite similar to the sun. One caveat, based upon solar analogy, is that in interpreting stellar observations we must expect short-lived radio phenomena may have vastly different properties, and may be sampling extremely different plasma conditions, depending on the wavelength of the observation. While the earliest detections of stellar flares occured at long wavelengths(430 MHz), most recent work has been done in the 1.4 Ghz to 5 GHz bands, especially since the advent of the VLA.

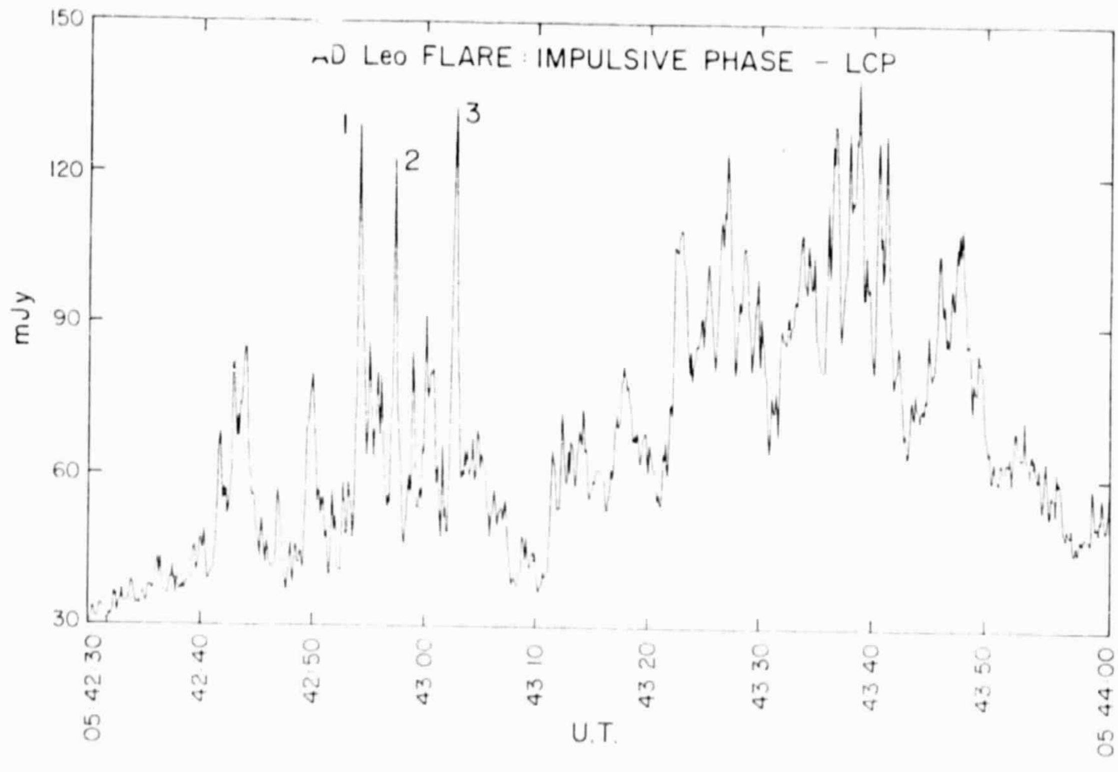
It is well accepted that solar and stellar activity at the chromospheric and coronal levels is a product of the magnetic field emerging from the stellar interior, and that this activity (at least in the solar case) is closely correlated with the active regions - i.e. spots and plages. Indirectly then, the observation and characterization of stellar flares may provide, via the constraints placed upon the magnetic fields involved with the flare, insights on the nature of stellar activity. One of the most pressing questions that can be asked (and answered only by stellar observations) is whether the near-equipartition of gas and magnetic pressure that is maintained by the sun is inherent to all solar-type stars (i.e., having surface convection zones). If so, then how does the magnetic field depend in detail on the two parameters most closely associated with stellar dynamos - the age and rotation rate of the star? To answer these questions will require a large amount of observing time dedicated to the task of establishing the statistical distribution of stellar flare energy (and perhaps other characteristics as well) as a function of event frequency from well chosen samples. Proper analysis of these distributions, to determine whether they can be represented by the solar distribution (and if not, determining which stellar parameters are responsible for the difference) will require the use of sophisticated statistical techniques. Thus, efforts should be made to extend detections of flares to all spectral types that are suspected of possessing solar-type closed magnetic structures (loops), since flares are typically associated with these features.

It is interesting to compare the highest time resolution observations yet reported for stellar radio flares with a solar example. Lang *et al.* (1983) observed an extremely strong flare (peak fluxes above 120 mJy at 1.4 Ghz) on AD Leo that contained very fine structures that were unresolved on timescales of 0.2 seconds (see Figure 1a). Similar solar observations (Slottje 1978,1980) show complex structure down to the millisecond level (Figure 1b) that is quite similar in appearance to the stellar flare. The importance of the Lang *et al.* observation lies in the high degrees of polarization and deduced brightness temperatures in excess of 10^{13} K, the first indication that coherent processes are responsible for (some of) the emission at this frequency. Care must be taken in making comparisons to solar microwave bursts, however. While the typical solar burst consists of an impulsive phase followed by a gradual component, the gradual component that followed the extremely spiky emission on AD Leo could not have been the stellar analog of the solar gradual phase (cf. Holman, Bookbinder and Golub 1984).

Longer wavelength observations also have shown the existence of fine time structure in both the solar and stellar cases. Solar bursts with fine structure on the order of 1 - 100 msec are observed at a wide variety of frequencies: below 1 Ghz (Slottje 1972), 1 to 1.4 GHz (Droge 1977), 2.6 GHz (Slottje 1978), 10 GHz (Hurford *et al.* 1979) and 22 and 44 GHz (Kaufman *et al.* 1980). Similarly, stellar bursts have been observed (usually with durations of less than a minute and variability on the order of a few seconds) at 196, 318 and 430 MHz (Spangler and Moffett 1976, Spangler, Shawhan and Rankin 1974) and 1.4 GHz (Lang *et al.* 1983). Since we are interested in the solar analogy, it may be worth noting from a solar example that variability may be best found by studying the polarized emission - in one example of a Type III burst, essentially no detailed structure was evident in the total intensity, but was present in the polarization (Pick *et al.* 1980, also Slottje 1974).

Furthermore, the timescale for the variability, if it does represent a real propagation effect (such as Alfven waves or slow-mode MHD waves), is

interesting for another reason as well, since it then measures the size of the coronal structure giving rise to the emission. The source dimensions can be estimated by assuming a spatial growth rate between the assumed propagation speed (e.g. the Alfven speed) and c. These would be the first measurements (albeit indirect) of the sizes of coronal loops on stars other than the sun. Through the use of HTR obervations, even without detailed knowldege of the source spectra and polarization, one can learn something about the microphysics of the flare plasma - i.e., the electron density, the magnetic field, the particle energy, etc (cf. Holman, Bookbinder and Golub 1984). The use of these diagnostics on a variety of active late-type stars, from dM through F (all of which are suspected to possess solar-like closed magnetic structures) can provide clues on the effects of the stellar parameters (such as efective temperature and surface gravity) on the stellar loops.



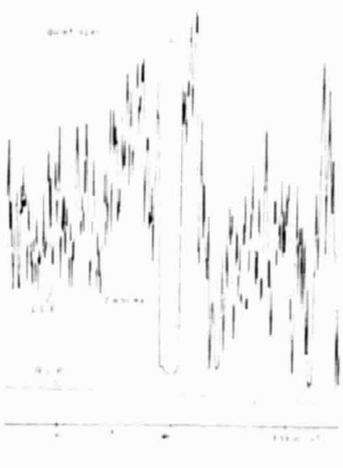


Fig. 1a. (above) A recording of the left circular polarization of a large flare observed on AD Leo at 1.4 GHz with 200 msec integration times. Note the extensive (and unresolved) structure (from Lang *et al.* 1983). The R.C.P showed no such variability, much like its counterpart in Fig. 1b.

Fig. 1b.(left) A solar observation at 2.65 GHz (after Slottje 1980). The two figures are displayed with the same scales for their abcissas. The similarities are striking.

Another important consequence of HTR observations are the restrictions on the particle acceleration mechanisms: the rise and decay times of the emission and (in the case of spike) the interspike period provide information. Most models prior to Slottje (1978) did not require acceleration mechanisms to be effective on timescales less than about a second. A number of theoretical mechanisms are available that can provide high brightness temperatures and spiky emission, such as gyrosynchrotron masering, stimulated plasma emission from the coherent interaction of electrostatic upper hybrid waves and the interaction of electron plasma waves (Holman 1983 and references therein). If we consider an electron-cyclotron maser, for example, the rise time of the emission reflects either the increasing number of electrons in the trap (i.e. the duration of the electron pulse), the saturation time of the maser, or else simply variations in the electric field itself. The decay time reflects either the decreasing heating rate or the e-folding time for the electrons to precipitate, whichever is shorter. The interspike period then is a measure of the timescale required to accelerate the electrons, the loop transit time or, more likely, represents the time during which the rather stringent conditions required for maser operation are not satisfied. Moreover, accurate knowledge of the brightness temperature can also specify the temporal form of the maser. For a maser with emission at the second harmonic to operate in a steady state condition requires that $T_B < 10^{14}$ K, though an intermittent maser can produce spikes with T_b up to 10^{18} K (Melrose and Dulk 1982).

One of the principal difficulties in studying the characteristics of stellar flares is the relatively low rate of strong flares from these stars - and of course, as one moves to smaller flares, one runs into the additional problem of distinguishing a flare from the noise in the signal. Fisher and Gibson (1981) provide rough estimates of flare frequencies (at 1.4 and 5 GHz) on the stars in the UV Ceti system: roughly one per 3.5 hours of observing. I have estimated the rate for AD Leo as one flare (greater than 20 mJy) per 8 hours at 1.4 GHz. Lovell (1963) has reported a flare rate of one flare per 35 hours at 240 Mhz, though this result is for very strong flares (about 1 Jy). From Spangler and Moffett (1976) and Spangler, Shawhan and Rankin (1974) we can estimate stellar flare frequencies at longer wavelengths for some of the more active M dwarfs. For Wolf 424 and YZ CMi, we obtain mean times between flares (greater than 0.5 Jy at 196 and 318 MHz and 1.5 Jy at 430 MHz) of 12,2.4,1 hours and 2.8,1.8,3 hours at 196,318 and 430 MHz respectively.

III. RS CVn Systems

Having looked at the information HTR can provide for us with respect to the solar-type stars, what can be said about the future of HTR observations for RS CVn systems? First, we note that HTR as applied to these objects involves timescales significantly longer than for the dM stars - and hence much easier to achieve in practice. Though the flare events generally occur on the timescales of hours to days, we note that observations of shorter-lived phemomenon are in the literature. Brown and Crane (1978) observed variations in the circularly polarized 2695 Mhz flux from V711 Tau on the order of a few minutes. Fix *et al.* (1980) have also observed variations of factors of two in the 1665 MHz flux on the order of several minutes. These observations provide us with an example of the different temporal behavior that can be found at different frequencies; Feldman (1983) reports that over 1000 hours of observing RS CVn

systems at 3 cm has shown none of the rapidly changing (highly) circularly polarized fluxes that have been reported at longer wavelengths (?? cm and ?? cm, respectively) by Feldman (1978) and Hjellming and Gibson (1980). The implication is that incoherent gyrosynchrotron emission seems adequate to explain the 3 cm emission, but that there is evidence for more exotic (coherent gyrosynchrotron or plasma emission) processes at the longer wavelengths.

It is also possible that HTR can be used to establish the nature of the quiescent emission from these systems. Mullan (1984) has indicated that, unlike for the flare stars, the flare-frequency vs. flare-energy curve of RS CVn systems is consistent with the hypothesis that their "quiescent" emission is really the superposition of a large number of small flares. More high time resolution observations could test this hypothesis more rigorously by searching for evidence of large numbers of small flares. HTR observations of these systems on timescales much less than a second will likely be useful only to study the initial phase of the larger flares, when the primary energy release is occuring, unless the flares really are a manifestation of the overall coronal heating process. Along the same lines, but at the other end of the energy scale, are the so-called "superflares", such as reported by Simon *et al.* (1980) Feldman (1983) and Hjellming and Gibson (1980), with flux densities on the order of 800 millijanskys (at 10.5 Ghz), which are prime candidates for HTR observations. Fine structure, on the order of tens of milliseconds, should be resolvable if it exists. Although the smoothness of the rise and fall of the so-called superflares argues strongly against an intermittently operating mechanism, higher time resolution of these flares might provide interesting counterpoint to the current theory.

There also exists one other controversial question about the RS CVn systems that can be addressed by these same observations - whether the cool spot that occurs represents a single active region or an association of several smaller, but energetically "independent" regions. Rosner and Vaiana (1978) have shown that it is possible to fit power laws to the flare-energy *vs.* flare-frequency curves for flares from many active stars under the assumption that the flaring is a stochastic relaxation phenomenon. Their model allows one to make inferences on the mode of energy storage and release. Such a fit to the radio flares from an RS CVn would indicate that the region is a single unit form the point of view of its energetics. However, if it is not possible to fit a single power law to the curve, then the spot is an agglomeration of several energetically independent active regions (i.e. the total energy involved in a flare should be related to the interflare duration). The use of this analysis is also pertinent to the question of the quiescent emission as discussed above.

V. Instrumentation

As we have pointed out above, the high time resolution that is needed in stellar observations must compete against the need to have sufficient signal to noise (i.e. long integration times). In general, stellar observations should be made at the highest possible time resolution and then intergrated up to provide sufficient signal-to-noise. Some single dish instruments (i.e. the 305m dish at Arecibo) can succesfully reduce their integration times to the region of interest (on the order of a tenth of a second or less), provided that signal has a reasonably high peak flux (cf. Lang *et al.* 1983, Boice *et al.* 1981). As usual with single dishes, confusion and terrestrial interference might be considered problems.

However, in searching for variability at these timescales the problem of confusing sources is negligible, and interference monitors have proven quite effective in discriminating between local signals and those of stellar origin (Spangler and Moffett 1976). Recently, proposals have been made (Stinebring 1984) that will permit extremely high time resolution observations using the VLA as a phased array, reaching down to about 20 microseconds from the current 3.3 second minimum integration time. Use of the VLA in this mode should be encouraged for all stellar observations, since it is run parallel to the aperture synthesis mode; i.e. maps can be made simultaneously with high time resolution flux measurements. It is worth stressing that the instrumental requirements for HTR radio observations do not demand major technological advances and can be easily met by existing technology (though perhaps at substantial costs).

VI. Summary

In conclusion then, we find that one of the main limitations on HTR observations is the refusal of stars to cooperate with the observer - i.e. low flare rates. Instrumental problems, mostly obtaining the necessary sensitivity (i.e. low noise) on short integration times is also a major problem, though not technically insurmountable. Few instruments are likely to be able to excel Arecibo or the VLA for this mode of observing. High time resolution observations are necessary to determine the nature of both the acceleration and emission mechanisms responsible for the short-lived radio phenomena that have already been observed. Further observations will undoubtedly provide us with novel events not familiar to us from the solar context. Besides the usual flare stars and RS CVn systems, it may be of interest to perform HTR observations on objects such as W UMa stars, PMS objects, OB stars, AM Her systems etc., all of which show evidence for non-thermal emission and/or short timescale variability.

References:

Abbott, D., Bieging, J. and Churchwell, E. 1984 these proceedings

Boice, D., Kuhn, J., Robinson, R. and Worden, S. 1981 *Ap.J.Lett.* **245**, L71

Brown, R.L. and Crane, P. 1978 *A.J.* **83**, 1504

Droge, F. 1977 *Aston. Astrophys.* **57**, 255

Feldman, P. 1983 in *Activity in Red-Dwarf Stars* ed. P. Byrne and M. Rodono D. Reidel, p. 340

Feldman, P., Taylor, A., Gregory, P., Seaquist, E., Balonek, T. and Cohen, N. 1978 *Astron. J.* **83**, 1471

Fisher, P. and Gibson, D. 1981 in *Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun. Vol II.*, eds. M.S. Giampapa and L. Golub, (Cambridge:SAO) p. 109.

Fix, J. Claussen, M. and Doiron, D. 1980 *Astron. J.* **85**, 1238

Gary, D., Linsky, J. and Dulk, G. 1982 *Ap.J.Lett.* **263**, L79

Gibson, D. 1984 these proceedings

Holman, G. 1983 *Adv. Space Res.* **2**, 181

Holman, G., Bookbinder, J. and Golub, L. 1984 these proceedings

Hjellming, R. and Gibson, D. 1980 in Proceedings of the IAU Symposium #86 *Radio Physics of the Sun*, eds. M. Kundu and T. Gergley, D. Reidel, p. 209

Hurford, G., Marsh, K., Zirin, H. and Kaufman, P. 1979 *BAAS* 11, 678

Kaufman, P., Strauss, F. and Opher, R. 1980 in Proceedings of the IAU Symposium #86
Radio Physics of the Sun, eds. M. Kundu and T. Gergley, D. Reidel, p. 209

Lang. K., Bookbinder, J., Golub, L. and Davis, M. 1983 *Ap.J.Lett.* **272**, L15

Lovell, B. 1963 *Nature* **198**, 228

Lovell, B. 1971 *Quart.J.R.A.S.* **12**, 98

Melrose D. and Dulk, G. 1982 *Ap.J.* **259**, 844

Mullan, D.J. 1984 these proceedings

Pick, M., Raoult, A. and Vilmer, N. 1980 in Proceedings of the IAU Symposium #86
Radio Physics of the Sun, eds. M. Kundu and T. Gergley, D. Reidel, p. 235.

Rosner, R. and Vaiana, G.S. 1978 *Ap.J.* **222**, 104

Simon, T., Linsky, J. and Schiffer, F. 1980 *Ap.J.* **239**, 911

Slottje, C. 1972 *Solar Phys.* **25**, 210

Slottje, C. 1974 *Astron. Astophys.* **32**, 107

Slottje, C. 1980 in Proceedings of the IAU Symposium #86
Radio Physics of the Sun, eds. M. Kundu and T. Gergley, D. Reidel, p. 209

Spangler, S. and Moffett, T. 1976 *Ap.J.* **203**, 497

Spangler, S., Shawhan, S. and Rankin, J. 1974 *Ap.J.Lett.* **190**, L129

Stinebring, D. 1984 Personal communication

NAGW-112

ON MAGNETIC FIELD STOCHASTICITY AND NON-THERMAL LINE BROADENING IN SOLAR FLARES

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ABSTRACT

We discuss observations of non-thermal line broadening seen in solar flares by the Solar Maximum Mission Satellite in light of recent results on the generation of magnetic field stochasticity. We show that a consistent model for the data can be constructed by assuming that the observations signal the destruction of an ambient magnetohydrodynamic equilibrium.

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I. INTRODUCTION

The spectroscopic capabilities of the *Solar Maximum Mission* (SMM), P78-1, and *Hinotori* satellites have led to a number of qualitatively new observations of solar flares, perhaps the most striking of which are the data on line broadening observed during the initial stages of flares (viz., Culhane *et al.* 1981, Tanaka *et al.* 1982, Doschek *et al.* 1985). In this paper we shall focus on one particular type of line broadening observation which we believe may hold a key to the processes which lead to the disruptive behavior characteristic of solar flares.

The onset of solar flares is characterized by large non-thermal broadening of soft x-ray lines emitted by highly ionized heavy ions, such as Ca XIX and Fe XXV. This effect is usually attributed to the presence of non-thermal plasma motions, and may be observed one or two minutes before the impulsive increase in hard x-ray flux (which traditionally marks the onset of flaring), and before the appearance of high-speed upflows of chromospheric material heated to coronal temperatures (chromospheric "evaporation"; Antonucci *et al.* 1982, 1984a). The excess line widths persist as long as there is observational evidence for energy release in the flare site. In the decay phase of flares, non-thermal velocities either are not observed, or are present at very low levels. The turbulence level in the plasma appears to be independent of the position of the flare on the solar disk.

A number of interpretations of these data are possible, the most commonly-accepted of which regard the overall line profile as a superposition of various Doppler-shifted components; this superposition is believed to be a result of an integration along the line-of-sight of various distinct, unresolved loop structures (or parts of loop structures). In this paper, we wish to pursue an alternative picture, in which the observed line broadening is due to a superposition of Doppler-shifted line profiles arising from distinct plasma flows originating within a *single* loop structure. We shall show that this hypothesis not only gives good account of the data, but also that it is a natural theoretical consequence of the lack of topological stability (viz., Tsinganos, Distler, and Rosner 1984) of coronal magnetic structures.

The structure of our paper is thus as follows. We first present a brief summary of the data (§ II), describe the model and apply it to the data (§ III), and then summarize our conclusions (§ IV).

II. THE DATA

High resolution spectroscopic observations of the thermal plasma formed during solar flares have been performed during the last solar maximum with the Solflex

experiment on the P78-1 satellite (Doschek *et al.* 1979), the Soft X-ray Polychromator on board the SMM satellite (Acton *et al.* 1980), and the SOX spectrometers on the *Hinotori* satellite (Tanaka *et al.* 1982). The data from these observations have shown that just before and during the impulsive phase (when energy is presumably first released), the width of soft X-ray spectral lines is larger than expected from the thermal broadening, as predicted from the electron temperature derived for the emitting plasma. This broadening effect is seen throughout the impulsive phase; however, the line broadening does decrease as the impulsive phase wanes, so that lines are thermal (or almost thermal) after the peak in soft X-ray flux (Doschek *et al.* 1980, Feldman *et al.* 1980, Antonucci *et al.* 1982, 1984a, Tanaka *et al.* 1982). These results are reviewed by Doschek *et al.* (1985).

The spectral regions preferentially observed by these experiments are those of the Ca XIX and Fe XXV helium-like resonance lines, formed at temperatures typical of flare plasmas (which are in the range $1\text{-}3\times10^7$ K). The satellite lines formed in the same spectral regions provide direct information on the electron temperature of the source (Gabriel 1972). Since the electron temperature is well-determined, the non-thermal excess in line width can be confidently derived. This excess cannot in general be attributed to a difference in ion and electron temperatures, because at the densities estimated for flare plasmas, the required temperature difference cannot be maintained for time-intervals as long as the flare rise times. The estimated turbulent velocity amplitude derived from the presumed Doppler temperature is between 100 to 200 km sec^{-1}. Non-thermal broadenings are also observed in cooler coronal lines and in transition lines (Doschek *et al.* 1985) during the impulsive phase.

Analysis of a large number of flares observed with the Bent Crystal Spectrometer of the SMM Soft X-ray Polychromator (Antonucci *et al.* 1984a) revealed the following key features:

1. *The non-thermal excess in line width is larger at flare onset, and decreases monotonically during the impulsive phase.* Thus, the maximum broadening is found to precede or to coincide with the peak in hard X-ray flux; in the decay phase, spectral lines are thermal, and late in the decay, the line width may increase again, with a velocity parameter of about 60 km sec^{-1}.

2. *The degree of non-thermal excess appears to be uncorrelated with the position of flares on the solar disk.* Thus, an average non-thermal velocity of 100 ± 40 km sec^{-1} is found for disk flares, and 120 ± 30 km sec^{-1} for flares at longitudes beyond 60°. Furthermore, limb flares (such as the flare of June 29, 1980) show non-thermal excesses comparable to that of flares observed on the disk.

3. ***When significant soft X-ray emission is detected before the hard X-ray burst, the non-thermal line broadening is observed to increase one or two minutes before the hard X-ray burst.*** **The increase in line width is in general accompanied by moderate intensity non-impulsive hard X-ray flux. This increase in line width for disk flares occurs before blue-shifted components are observed in the spectra (note that the blue shifts are observed to be simultaneously with the impulsive increase in hard X-ray emission at burst onset). These blue shifts are usually interpreted as the signature of high-speed upflows of chromospheric material as it is heated to coronal temperatures during the "evaporation" process (Antonucci *et al.* 1982).**

The particularily well-observed flare of May 21, 1980 typifies these characteristics. In this event, which was not preceded by any detectable soft X-ray emission at temperatures of 10^7 K from the active region, it is possible to clearly distinguish the initial phase, characterized by non-thermal velocities of about 220 km sec^{-1} and moderate intensity hard X-ray flux, from the impulsive increase in hard X-ray emission and the onset of plasma upflows, as shown in figure 1. At this stage, soft X-rays are emitted predominantly from one of the two footpoints of the flaring loop system (Antonucci *et al.* 1984', c). Flare footpoints can be cl arly identified in a second stag , in coincidence with the impulsive increase in hard X-ray flux, when localized hard X-ray sources appear in correspondence with the Hα kernels. This emission is thought to be due to energy deposition at the loop base by non-thermal electrons (Hoyng *et al.* 1981).

The first spectrum obtained during the May 21 event in the Ca XIX spectral region, averaged over a two-minute period, is shown in Figure 2a. The initial time of the observation period is 20:53:02 UT. Spectral features are not resolved due to the large non-thermal broadenings, and the profile of the resonance line is consistent with a Doppler temperature of 1.3×10^8 K, while the inferred electron temperature is only 9×10^6 K. The difference in Doppler and electron temperatures implies a non-thermal velocity of 220 ± 30 km sec^{-1}. This initial Calcium spectrum is to be compared with the spectrum obtained at the peak of the soft X-ray flare (Figure 2b). The continuous curves superimposed on the data are synthetic spectra computed as described in Antonucci *et al.* (1982).

The soft X-ray image in the energy band from 3.5 to 8 keV of the flare region in the initial state at 20:53:02 UT (as obtained with the SMM Hard X-ray Imaging Spectrometer; van Beek *et al.* 1980) is shown in Figure 3. The spectrometer has a spatial resolution of 8". Points A and B in Figure 3 indicate the position of the footpoints of the flaring loop system inferred from the hard X-ray images in the energy band from

16 to 30 keV, detected by the same instrument at 20:55:06 UT. The dominant feature around footpoint B has an area of approximately 1.4×10^{18} cm^2, and emits 30% of the total flux. The soft X-ray image at 20:55:06 UT, simultaneous with the appearance of the hard X-ray footpoints, indicates that initially the thermal plasma is denser close to the base of the flaring loop system.

The temporal variation of the turbulent velocity derived from the Calcium spectra is compared in Fig. 1 with the hard X-ray emission detected by the SMM Hard X-ray Burst Spectrometer (Orwig *et al.* 1980). The emission is integrated over the energy band from 25 to 386 keV. Significant non-thermal velocities are observed as long as the hard X-ray flux remains at high level, and has a hard spectrum, that is, as long as there is significant energy release in the flare region. The time variation of the velocity of plasma upflows, as derived from the observed blue shifts, is also shown in Fig. 1.

III. A NON-THERMAL FLARE LINE BROADENING MODEL: MAGNETIC STOCHASTICITY

How are these data to be interpreted? While there is consensus on the association of the excessive line broadening with mass motions, the nature of these mass motions is not as well established. In this section, we begin by briefly reviewing one common explanation for the broadening, as set out most recently by Doschek *et al.* (1985); our aim is to show that this most straightforward model does leave unexplained several crucial features of the data, which will figure prominently in defining our model.

a) The Simplest Model for Non-thermal Line Broadening.

Let us first consider the most straightforward explanation for the observed broadening. As discussed by Doschek *et al.* (1985), broadened lines may result because of convective flows within loops, which originate during the "evaporation" phase. This interpretation is suggested by the fact that both non-thermal motions and plasma upflows in the active coronal loops are observed only during the impulsive phase, and by the correlation between the peak values of the isotropic non-thermal and upward flow velocities. Furthermore, numerical simulations of flaring loops (see, for example Peres *et al.* 1985) predict line broadening (as well as blue-shifted spectral components), even for the case of a single loop configuration; in the case of the single loop, the broadening results when the flare heating spatial dependence (Cheng *et al.* 1984) or the loop geometry itself is asymmetric, and can also arise for certain projections of the loop with respect to the line-of-sight. Moreover, it has been argued that a much more plausible flare configuration than a single "flare loop" is a complex of loops which

participate in the flaring process. In this more realistic case, the line broadening from convective flows is yet more easily achieved because the superposition of the contributions of a distribution of loops (and their associated convective flows) within a resolution element must be taken into account. In favor of this interpretation is also the fact that line broadening decreases with decreasing temperature, which is to be related to the lower evaporation velocities expected for cooler material (Doschek *et al.* 1985). In summary, it seems to us that there is no doubt that introduction of sufficient geometric complexity can allow the above model to account for the data. However, given this necessary geometric complexity, it seems worthwhile to ask whether a more economic explanation for the phenomena is available. To better define the requirements for such an exlanation, consider the major observational challenges faced by the geometric models:

1. *Lack of a longitude dependence of the isotropic turbulent flow parameters.* If "evaporation" is the cause of the convective motions which lead to the line broadening (as well as to the blue wings), we would expect some dependence of line width on the flare longitude (because the flows induced by the "evaporation" process are dominantly vertical to the solar surface). This expected effect would be most pronounced for limb flares. It is relatively trivial to model this behavior: Assume that the evaporative flow within a single loop is described by the blue-shifted component seen disk-on, and further assume that the flare site is a composite of loops with a uniform distribution in the angle between the solar surface normal and the normal to the loop plane (so that the loops are on average inclined to the solar surface at angles between 0 and $\pm\pi/2$). In this most favorable case (because it includes the implausible case of loops lying parallel to the solar surface), the convolution of the projected velocity distribution with the loop orientation distribution yields a predicted line profile at disk center which will not show any red wings (see 2. following), but will show a blue wing. In contrast, unless there is a strong asymmetry of flows within loops, a flaring region at the limb will show only weak blue wings (as well as weak red wings). Indeed, the data do show that the transient blue component (which is most naturally associated with the "evaporated" material) is not observed in limb flares. If the non-thermal broadening is in fact related to these upflows, one would then expect at least some corresponding decrease in its contribution to the observed line profile in limb flares (as the systematic blue wing is absent): however, the available data do not confirm either this effect, or the existence of any correlation between the broadening and the angle between the line-of-sight and the local radial direction in the immediate vicinity of a flare. Thus, the available data do suggest that the turbulent motion field within the loop(s) is

isotropic, at least to the accuracy which can be attained to date.

2. ***Symmetry of the broadened line for on-disk flares.*** The dominant changes in the Ca XIX line at flare onset are the strong increase in intensity and the substantial symmetrical broadening of the line about line center, the latter independent of flare location on the disk. We find it physically implausible to construct an ensemble of flaring loops such that the observed Ca XIX line emission receives *equal* contributions from up and down flowing large-scale flows independent of the flare location (as required by the line symmetry). Asymmetries in the impulsive heating within any given loop can lead to flows of opposite sign near the loop's two footpoints (S. Antiochos, private communication), but it is unlikely that such asymmetries *always* arrange themselves so that the emission measure contributions from up and down flowing material are always identical (to present experimental uncertainties). Antiochos has also suggested that during the initial heating phase (before evaporation has occured), the expansion of heated pre-existing coronal material will lead to an initial phase of downflows near the loop footpoints (as in fact seen and discussed, for example, in the simulations reported by Peres *et al.* 1985); however, this effect (which does explain the red-shifted portion of the broadening) fails to account for the comparable blue-shifted portion of the broadening.

3. *Relative Timing of non-thermal broadening and blue shifts.* Non-thermal velocities are often observed *before* the appearance of high-speed upflows (i.e., before the appearance of significant blue wings; Figure 1); certainly, the emission which occurs this early during the rise phase cannot be easily explained in terms of a distribution of convective velocities driven by the "evaporation" process (see also 2. above). In this initial phase, moreover, the non-thermal velocities are quite large; indeed, the associated line broadening (together with a moderate flux of hard X-rays) is often the first evidence for flare onset as seen by looking at high-energy photons.

In summary, observations of individual flares indicate the presence of fairly isotropic flows during the early part of flare onset; these flows exist in addition to the systematic upward flows (which are most likely related to the initial "evaporation" of chromospheric material). The lack of any longitude dependence of both the red and blue wings of the line broadening for different flares and its symmetry suggests that the broadening is indeed isotropic (and not simply due to a superposition of Doppler-shifted components which arise within distinct, but unresolved, loops); the timing of the onset of strong line broadening calls into question its association with the evaporation process; and the fact that broadening occurs (and is largest) at the very onset of the flare argues that it is pre-existing (not newly-evaporated) coronal material which is

responsible for the line broadening. Our arguments thus support the proposition that the observed broadening appears isotropic not because of accidental superposition of various unresolved flaring loops (and associated interior convective flows) along the line-of-sight, but because the fluid which gives rise to the observed emission is indeed isotropically turbulent in any one given loop structure (i.e., the fluid is, on the dimensions of the loop, locally isotropically turbulent).

The idea that the observed broadening is the result of locally-isotropic motions within well-defined, local regions in a loop is not new, and in fact underlies the recent "maser" model of Melrose and Dulk (1984). They suggest that the flaring coronal plasma can be heated to temperatures of $\approx 10^7$ K through local absorption of photons produced by direct production of electromagnetic radiation via a gyrosynchrotron loss cone instability (*viz.*, Wu and Lee 1979). This instability is thought to occur in a large number of small regions, resulting in short elementary bursts; its end result is to transform the free energy residing in the perpendicular (to $\vec{B}$) motions of mirrored (reflected) accelerated electrons to radio frequency radiation. The localized heating in the flare region leads then to rapid expansion of the heated plasma at speeds up to the ion sound speed; this expansion may account for the observed non-thermal line broadening. Thus, in this model non-thermal motions, and the associated line broadening, are expected as long as the hard x-ray emission is observed. In the next section, we propose an alternative picture, which also leads to fairly isotropic motions within any one given loop right at flare onset.

b) Field Line Stochasticity and The Onset of Flare Fluid Turbulence.

It has been long recognized that it is very difficult to construct stable magnetostatic (or magnetohydrodynamic) equilibria; that is, it has not in general been possible to devise such equilibria (other than for configurations having a high degree of symmetry) in a systematic manner (see, for example, Manheimer and Lashmore-Davies 1984 for a review of plasma equilibria and their stability properties). This has led to the conjecture that this difficulty is not simply computational, but rather is generic, i.e., that lack of equilibrium states for geometries that have no simple spatial symmetry is a fundamental property of magnetofluids (Grad 1967; Parker 1972, 1979). This conjecture has recently received theoretical support from the demonstration that in the absence of rigid boundaries and gravity, symmetric magnetostatic equilibria are topologically unstable (Tsinganos 1983; Rosner and Knobloch 1983; Tsinganos, Distler, and Rosner 1984); that is, such equilibria have the property that (except for a special class of perturbations of zero measure) arbitrary perturbations necessarily lead to a violation of the

magnetostatic constraint - pressure surfaces no longer coincide with magnetic flux surfaces - so that the system becomes dynamic. Typically, the symmetry of the original equilibrium is broken because singular points arise within the configuration and, as shown by Parker (1982, 1983; see also Vainshtein and Parker 1984), static equilibrium is not possible in the vicinity of such new singular points. Thus, the imposition of external perturbations on an equilibrium MHD structure leads to a situation in which the system locally departs from static conditions, and local reconnection occurs (cf. reviews by Freiberg 1982 and Manheimer and Lashmore-Davies 1984). In the context of laboratory plasma confinement, this process is related to the destruction of magnetic surfaces and the formation of magnetic islands; in the context of heating the solar corona, Parker (1983) has argued that such a situation arises in the lower solar atmosphere due to the continual deformation of the coronal magnetic fields by the horizontal cellular photospheric flow field. In summary, local disequilibrium (i.e. lack of local static equilibrium) leads naturally to formation of localized reconnection regions and initially isolated magnetic islands throughout the loop volume.

What is the consequence of this local destabilization in the context of a single flaring loop? We conjecture that the system will continue to evolve quasi-steadily (consistent with the field line topology imposed by the perturbation) until island formation has proceeded sufficiently to produce regions of overlapping islands; this leads to the onset of field line stochasticity, strongly enhanced local reconnection and dissipation, and enhancement of plasma transport coefficients (cf. Freiberg 1982; a related process, proposed in the context of a specific MHD instability, e.g. island overlap of unstable tearing modes located in distinct unstable tearing layers, has been proposed by Finn 1975, and applied to the flare onset problem by Spicer 1975, 1976). It is essential to distinguish this succession of events from the destabilizing process previously suggested by Low (1982a,b) and others, who have argued that solar flares represent the terminal point of an evolutionary sequence of "nearby" equilibria through which a system evolves as it is subjected to external perturbations; this terminal point is reached when the sequence of equilibria ends in the sense that there are no longer any nearby equilibria to which the system could evolve. Our model is distinguished from these earlier studies in that (i) we do not identify the onset of flaring with the point of termination of a sequence of nearby equilibrium states, but rather view it as the point at which a topological unstable, quasi-steadily evolving state (which need not be force-free; compare with Heyvaert and Priest 1983) reaches the stochastic domain; and (ii) the instability in our picture does not manifest itself in a global MHD instability, but rather in a drastic departure from statics throughout the entire volume of the system, wherever

singular field line behavior as a result of island overlap, and local reconnection, occurs. These localized reconnection events are then expected to occur at the very onset of the flare -- indeed, in our picture, they mark the very beginning of flare onset.

In the same connection, Parker (1983) has followed the hydrodynamics of a layer of fluid confined by the pressure of the reconnecting magnetic fields, and found initial acceleration of the fluid and formation of jets that "squirt" away from the reconnection site, leading eventually to a quasi-static configuration characterized by jet deceleration and simpler magnetic topologies. If this "microscopic" picture of the reconnection dynamics applies to the reconnection sites we presume are distributed throughout the flare loop volume, we can decide quantitatively whether the observations of line broadening are consistent with the our model, and what conclusions regarding the nature of the reconnection regions can be drawn. Specifically, consider the May 21 flare discussed above, for which the necessary data are in hand. Comparison of HXS and magnetograph data (the latter obtained at 20:15 UT, courtesy of J. Harvey) shows that at the flare site, the mean photospheric magnetic field strength at one of the flare loop footpoints (marked A in Figure 1d of Hoyng *et al.*) is $\approx$ 160 Gauss, covering an area of $\approx$ $7.4\text{x}10^{17}$ cm^2. From SXR images, we estimate that the loop cross-sectional area expands to $\approx 1.4\text{x}10^{18}$ cm^2 in the low corona; if magnetic flux is conserved, then a reasonable estimate of the coronal field strength is $\approx$ 80 Gauss. From XRP data (taken between 20:53-20:55 UT), we estimate an emission measure of $\approx 5\text{x}10^{48}$ cm^{-3}, so that with the dimensions given above, we obtain an estimate for the coronal plasma density, $n_e \approx 3\text{x}10^{10}$ cm^{-3}. Thus, we can finally estimate the Alfven speed in this region; we find $v_A \approx 1\text{x}10^8$ cm sec^{-1}. This compares with the observed turbulent broadening velocity v_t of $\approx 2.2\text{x}10^7$ cm sec^{-1}; as expected, $v_A \gtrsim v_t$.

Now, if the broadening is indeed due to the superposition of random outflows (whose rate ought to be of the order of the Alfven speed) in many reconnection sites, then we would expect that $v_A \sim v_t$; this can be true only if the estimate of the plasma density in the reconnection site used above is in error (it is unlikely that our estimate of the field strength is so seriously in error). A moment's reflection shows why the above estimate for n indeed <u>ought to be in error</u>: we assumed that the emission measure is associated with the entire $(16'')^3$ coronal volume estimated from the SXR images, with a filling factor of unity, even though the model asserts that the emission is in fact coming from a large number of small-scale reconnection sites scattered throughout the volume of the flaring loop. To be consistent, we thus equate v_A and v_t, and then determine n: we obtain $n \approx 6.6\text{x}10^{11}$ cm^{-3}. This implies that the filling factor is in fact $\approx$ 5% of the total volume seen by the SXR in emission.

Now, the flows ejected by the localized reconnection regions will take some time to dissipate in the low-viscosity corona; in fact, in the absence of turbulent mixing (which will further contribute to the isotropization of the turbulent flows), the shortest relevant time scale for stopping these flows is the geometrical crossing time: if we estimate the length of the entire loop (from footpoint to footpoint) to be of order 10^{10} cm, then this time scale is roughly 450 sec. This is consistent with the e-folding decay time of the observed turbulent velocity v_t, $\tau \approx 400$ sec.

IV. SUMMARY

In this paper, we have put forth an alternative model for the recent observations that solar flares are accompanied by line broadening at the very onset of the flare, i.e., earlier than one would expect any significant "evaporation" of plasma from the loop footpoints. We briefly recapitulate recent theoretical work on the topological stability of magnetic structures, which suggests that departures from static equilibrium should be accompanied by the formation of singular points and magnetic islands throughout the volume of the plasma, and that when island overlap occurs, field line stochasticity and localized reconnection result, manifesting themselves by onset of vigorous flows near the localized reconnection regions. We suggest that it is the superposition of these flows associated with local reconnection sites scattered throughout the flare loop which leads to the observed line broadening. More particularly, we showed that the observations are quantitatively consistent with a model in which the turbulent broadening of high-temperature plasma is entirely due to the outflowing motions from reconnection sites scattered throughout the flaring loop.

The model we propose to account for the turbulent line broadening has several additional attractive features. The most obvious is that the reconnection sites we invoke to account for the macroscopic plasma streaming will also be sites of localized particle acceleration. As discussed in § II, hard x-ray bursts are observed precisely during the period in which turbulent line broadening is observed; in our model, the fast particles which give rise to the bursts may have their origin in the many scattered reconnection sites we've invoked. In particular, this implies that particle acceleration does not occur at just a very few selected sites within a loop, but rather occurs throughout the loop volume. An especially interesting possibility is then that particles accelerated in any one such reconnection region continue to be accelerated in other reconnection regions they encounter as they traverse the loop; such multiple acceleration encounters may provide the Fermi process called for by the particle spectra deduced from the SMM hard x-ray and gamma ray observations (viz., Ramaty *et al.* 1983, and references therein).

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BIBLIOGRAPHY

Acton, L. W., *et al.* 1980, *Solar Phys.*, **65**, 53.

Antonucci, E. 1982, *Mem. S. A. It.*, **53**, 495.

Antonucci, E., *et al.* 1982, *Solar Phys.*, **78**, 107.

Antonucci, E., Gabriel, A. H., and Dennis, B. R. 1984a, *Ap. J.*, in press.

Antonucci, E., Marocchi, D., and Simnett, G. M. 1984b, *Adv. Space Sci.*, in press.

Antonucci, E., Dennis, B. R., Gabriel, A. H., and Simnett, G. M. 1984c, *Solar Phys.*, in press.

Cheng, C. C., Karpen, J. J., and Doschek, G. A. 1984, *Ap. J.*, submitted.

Culhane, J. L., *et al.* 1981, *Ap. J. (Letters)*, **244**, L141.

Doschek, G. A., Kreplin, R. W., Feldman, U. 1979, *Ap. J.*, **233**, L157.

Doschek, G.A., *et al.* 1985, in **SMM Workshop Proceedings**, "Chromospheric Explosions", in press.

Feldman, U., Doschek, G. A., Kreplin, R. W., and Mariska, J. J. 1980, *Ap. J.*, **241**, 1175.

Finn, J. M. 1975, *Nucl. Fusion*, **15**, 845.

Freiberg, J. P. 1982, *Rev. Mod. Phys.*, **54**, 801.

Gabriel, A. H. 1972, *M.N.R.A.S.*, **160**, 99.

Grad, H. 1967, *Phys. Fluids*, **10**(1), 137.

Heyvaerts, J., and Priest, E. R. 1983, *Astron. Astrophys.*, **117**, 220.

Hoyng, P., *et al.* 1981, *Ap. J. (Letters)*, **246**, L155.

Low, B. C. 1982a, *Rev. Geophys. Space Phys.*, **20**, 145.

Low, B. C. 1982b, *Solar Phys.*, **77**, 43.

Manheimer, W. M., and Lashmore-Davis, C. 1984, *NRL Report.*

Melrose, D. B., and Dulk, G. A. 1984, *Ap. J.*, **282**, 308.

Orwig, L. E., Frost, K. J., and Dennis, B. R. 1980, *Solar Phys.*, **65**, 25.

Parker, E. N. 1972, *Ap. J.*, **174**, 499.

Parker, E. N. 1979, **Cosmical Magnetic Fields** (Oxford: Clarendon Press).

Parker, E. N. 1982, *Geophys. Astrophys. Fluid Dyn.*, **22**, 195.

Parker, E. N. 1983, *Geophys. Astrophys. Fluid Dyn.*, **24**, 79.

Peres, G. *et al.* 1985, in **SMM Workshop Proceedings**, "Chromospheric Explosions", in press.

Ramaty, R. *et al.* 1985, in **SMM Workshop Proceedings**, "Chromospheric Explosions", in press.

Rosner, R., and Knobloch, E. 1983, *Ap. J.*, **262**, 349.

Spicer, D. S. 1976, Naval Reseach Lab. Rept. No. 8036.

Spicer, D. S. 1977, *Solar Phys.*, **53**, 305.

Tanaka, K., Watabane, T., Nishi, K., and Akita, K. 1982, *Ap. J.*, **254**, L59.

Tsinganos, K. 1983, *Ap. J.*, **259**, 832.

Tsinganos, K., Distler, J., and Rosner, R. 1984, *Ap. J.*, **278**, 409.

Vainshtein, S. I., and Parker, E. N. 1984, preprint.

Van Beek, H. F., Hoyng, P., Lafleur, B., and Simnett, G. M. 1980, *Solar Phys.*, **65**, 39.

Wu, C. S., and Lee, L. C. 1979, *Ap. J.*, **230**, 621.

FIGURE CAPTIONS

Figure 1: Temporal evolution of the impulsive hard X-ray (HXR) emission in the energy band from 25-386 keV, detected by the Hard X-ray Burst Spectrometer; of the upflow velocity v' and of the turbulent velocity v_t in the soft X-ray (SXR) plasma, inferred from the spectra detected in the Calcium channel (3.165-3.231 A) of the Bent Crystal Spectrometer. The period of observation of the first spectrum of Figure 2 is also indicated.

Figure 2: Comparison of two X-ray spectra obtained with the Bent Crystal Spectrometer on SMM before the impulsive hard X-ray increase, at 20:53:02 UT, (a), and at the peak of the thermal phase at 21:07:00 UT, (b), of the May 21, 1980 solar flare. The smooth curves represent synthetic spectra computed for the given values of electron temperature T_e and Doppler temperature T_D.

Figure 3: Soft X-ray images of the 21st of May 1980 flaring region obtained in the 3.5-8 keV energy band of the Hard X-ray Imaging Spectrometer. The images are deconvolved to allow for the triangular response of the spectrometer collimator. The crosses represent the positions of the emission peaks measured in the hard X-ray images in the 16-30 keV band. The contour levels correspond to 14, 26, 40, 55, 70, 80, 90, 98 and 100% of the peak counting rate.

IMPLICATIONS OF THE 1400 MHz FLARE EMISSION FROM AD LEO FOR THE EMISSION MECHANISM AND FLARE ENVIRONMENT

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High brightness temperature spikes have been observed during a radio flare on the M-dwarf flare star AD Leo (Lang et al. 1983). Their high brightness temperature ($>10^{13}$ K) and circular polarization indicate that a coherent radiation mechanism must be responsible for the spike emission. The underlying flare emission, which is identified with a low polarization, gradual component, was found not to be spiky to within the 200 ms time resolution of the observations. This note is concerned primarily with this non-spiky emission.

The non-spiky emission is about 100 times more intense than the most intense solar flare emission at 1400 MHz, and about four orders of magnitude more intense than a typical solar flare. The brightness temperature of the emission is

$$T_B = 6.41\times10^{10}(S/f^2)(d/R)^2 \quad ,$$

where S is the radio flux at frequency f in Janskys, f is in GHz, d is the distance to the star in parsecs (4.9 pc for AD Leo), and R is the linear size of the source region in solar radii. Taking R to be less than the stellar radius (approximately half the radius of the sun), the brightness temperature is found to be $T_B > 3\times10^{11}$ K. Hence, the brightness temperature of the non-spiky emission is also quite high, and a nonthermal emission mechanism is required.

The emission mechanism for the non-spiky emission may be either incoherent synchrotron radiation or coherent gyrosynchrotron or plasma radiation. Independent of whichever mechanism is responsible, the 1400 MHz observing frequency puts constraints upon the density and magnetic field strength in the emission region. In order to avoid suppression of the radiation by the thermal plasma, the thermal electron density is constrained to $n < 1.24\times10^{10}f^2(\mathrm{GHz}) = 2.4\times10^{10}\ \mathrm{cm}^{-3}$. For synchrotron or gyrosynchrotron emission, the electron gyrofrequency must be smaller than the observation frequency, giving $B < 357f(\mathrm{GHz}) = 500$ G. Also, the synchrotron loss time becomes shorter than the 15 min rise time of the flare if $B > 500$ G. Even if the emission mechanism does not directly

involve the magnetic field, this condition is required to avoid thermal cyclotron absorption of the radiation. Therefore, the magnetic field strength in the emission region is comparable to or not much greater than a value that is characteristic of solar coronal loops in active regions.

If the emission is assumed to be incoherent synchrotron radiation, the source size and magnetic field are constrained by the fact that the source size cannot be smaller than the size that is required for it to become self-absorbed at the observation frequency. This constrains the linear size of the source to (cf. Pacholczyk 1970, Ramaty and Petrosian 1972)

$$R \gtrsim 3.3\, S^{1/2} B_{\perp}^{1/4} f^{-5/4} d \quad ,$$

where $B_{\perp}$ is the component of the magnetic field transverse to the direction of wave propagation and R, S, f, and d are in the same units as above. For the AD Leo flare this gives $R \gtrsim 3.4 B_{\perp}^{1/4}$. Hence, for $B_{\perp}$ = 100 G, $R \gtrsim 20$ stellar radii. Even for $B_{\perp}$ as low as 1 G, $R \gtrsim 7$ stellar radii is required. Taking $B_{\perp}$ = 1 G, the brightness temperature of the emission is $T_B \gtrsim 7\times10^9$ K and electron energies of at least 1 MeV are required. In summary, for incoherent emission, either a very large (>10 stellar radii) "magnetospheric" source region containing mildly relativistic electrons and ~100 G magnetic fields is required, or a smaller source of low magnetic field strength ($\lesssim$1 G) and fully relativistic electrons is required. In either case, the conditions are quite distinct from those that characterize the impulsive microwave emission from solar flares (cf. Kundu 1965).

An attractive coherent mechanism for the non-spiky emission, as for the spikes, is gyrosynchrotron masering from electrons reflected in a magnetic loop (Holman, Eichler, and Kundu 1980). As was noted by Lang et al., second harmonic emission requires a magnetic field strength of 250 G. An interesting possibility is that the spiky and the non-spiky (which may in fact be spiky on a time scale less than 200 ms) emissions are masering at adjacent harmonics, with the non-spiky emission arising from the higher harmonic. Alternatively, the radiation may be plasma emission at twice the electron plasma frequency or at twice the upper hybrid frequency (see Holman 1983 for a review). Emission near the plasma frequency itself is not as likely, since free-free absorption in the overlying stellar atmosphere is strong. The magnetic field and plasma parameters that are required by each of these mechanisms are comparable to those that are characteristic of flaring regions in the solar corona.

In conclusion, the AD Leo flare emission is clearly not analogous to the impulsive phase microwave emission from solar flares. On the other hand, the high brightness temperature, presence of superimposed spikes, and observing frequency are consistent with the properties of solar decimetric Type IV bursts (see Kundu 1965, Kuijpers 1980). The coherent emission mechanisms are difficult to distinguish observationally, since they all produce high brightness temperature,

narrow bandwidth, highly polarized emission. The different mechanisms do depend upon different physical parameters, such as magnetic field strength for gyrosynchrotron masering a electron density for coherent emission at twice the electron plasma frequency, and could be distinguished if the values of these parameters in the emission region could be independently determined. The possibility that the emission is incoherent synchrotron radiation can be tested with polarization, timing, spectral, and high spatial resolution (VLBI) measurements, however, since incoherent emission from relativistic electrons would not be consistent with a high degree of circular polarization, rapid variability would not be consistent with the large source size that is required, and narrow-band spectral features would be indicative of a coherent mechanism.

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REFERENCES

Holman, G. D., Eichler, D., and Kundu, M. R. 1980, in IAU Symposium No. 86, "Radio Physics of the Sun", M. R. Kundu and T. E. Gergeley, eds. (Dordrecht: Reidel), p. 457.

Holman, G. D. 1983, Adv. Space Res., Vol. 2, No. 11, 181.

Kuijpers, J. 1980, in IAU Symposium No. 86, "Radio Physics of the Sun", M. R. Kundu and T. E. Gergely, eds., p. 341.

Kundu, M. R. 1965, Solar Radio Astronomy (New York: Interscience).

Lang, K. R., Bookbinder, J., Golub, L., and Davis, M. M. 1983, Ap. J., 272, L15.

Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: W. H. Freeman).

Ramaty, R. and Petrosian, V. 1972, Ap. J., 178, 241.

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EINSTEIN X-RAY SURVEY OF THE PLEIADES: THE DEPENDENCE OF X-RAY EMISSION ON STELLAR AGE

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ABSTRACT

Two 1° × 1° fields of the Pleiades region, containing 78 cluster members within a limiting magnitude of 14 mag and centered on two of the most luminous stars of the cluster (20 Tau and 17 Tau) have been observed with the *Einstein* (*HEAO 2*) *Observatory* imaging proportional counter. The exposure times (~ 3–4×10^3 s) and background level give, at the Pleiades distance (~ 127 pc), a mean detection threshold of $10^{29.5}$ ergs s^{-1}. We have detected one (out of eight) B stars, one (out of 13) A stars, two (out of 10) F stars, 11 (out of 21) G stars and six (out of more than 26) K stars. The brightest X-ray source is Hz II 253 (G1), with $L_x \approx 10^{30.3}$ ergs s^{-1}.

We derive the maximum-likelihood X-ray luminosity functions for the G and K stars in the cluster, and show that for the G stars, the Pleiades X-ray luminosity function is significantly brighter than the corresponding function for Hyades G dwarf stars. The significantly larger number of X-ray bright G stars than K stars (even though the Pleiades K stars appear to be relatively rapid rotators), and the lack of detection of M stars, suggest that the connection between stellar rotation and the level of X-ray emission is not as straightforward as has been heretofore thought.

Subject headings: clusters: open — stars: rotation — X-rays: sources

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I. INTRODUCTION

One of the most striking features of stellar X-ray emission discovered with the *Einstein* (*HEAO-2*) *Observatory* is the fact that stars of the same spectral type and luminosity class emit over a wide range. Since the internal structure and the photosphere of stars of a given spectral type and luminosity class are similar, the range of X-ray emission observed can only be explained by relating it to other physical stellar parameters which do not traditionally figure in placing stars in the H-R diagram.

For example Pallavicini *et al.* (1981, 1982), among others (see also Walter 1981), have investigated the dependence of X-ray luminosity on stellar rotation rates for a large sample of X-ray sources, and have found that most of the variance in the emission levels of stars for spectral types later than F7 can be related to the observed dispersion in rotation rates. Thus they find that the X-ray luminosity is quadratically related to the stellar rotation rate or, more specifically, that $L_x \approx (v \sin i)^{2.0}$, where L_x is the X-ray luminosity and $v \sin i$ is the equatorial rotation speed projected along the line of sight. This result can be understood qualitatively by assuming that the mechanism responsible for heating the outer atmosphere of late-type stars to temperatures of several million K is related to dissipation of energy in magnetic-fueld–dominated regions at the stellar surface. The stellar rotation therefore enters in the above relation because in stellar dynamo theory it is one of the important

parameters which determine the rate of magnetic-field generation in the stellar interior. Similar arguments can be made regarding the observed correlation between stellar activity indicators and Rossby number (cf., Noyes *et al.* 1984; Schmitt *et al.* 1985; Micela, Sciortino, and Serio 1984; Serio 1984). 231

Since stars lose their angular momentum in the course of their evolution, it is also reasonable to investigate the dependence of X-ray luminosity on stellar age. Stern *et al.* (1981) have in fact surveyed the Hyades open cluster, which has an age of $\sim 6 \times 10^8$ yr, and have found that the median X-ray luminosity (L_x) of G stars in this cluster is ~ 30 times larger than that of the Sun, consistent with a quadratic dependence of L_x on stellar age. In contrast, Ku and Chanan (1979). Feigelson and De Campli (1981), and Montmerle *et al.* (1983) have observed pre-main-sequence G stars in regions of recent star formation, whose median X-ray luminosity ($\sim 10^{31}$ ergs s^{-1}) suggests a linear decay of L_x with stellar age; a similar result was obtained by Micela *et al.* (1983) from preliminary analysis of X-ray observations of stars in the Pleiades. This paper addresses the question of the stellar activity–age relation by examining the complete results of an *Einstein* X-ray survey of the central region of the Pleiades, a well-known galactic open cluster somewhat younger than the Hyades.

Our paper is organized as follows: we describe the data selection procedures, the method of analysis, and the results of the survey in the next section. The implications of these results for the dependence of X-ray emission from late type stars on the properties of the underlying star are discussed in § III. Our results are summarized in § IV.

II. DATA SELECTION, METHOD OF ANALYSIS, AND RESULTS

Two *Einstein* IPC (Gorenstein, Harnden, and Fabricant 1981; Giacconi *et al.* 1979) exposures centered on two of the brightest stars of the Pleiades (17 Tau and 20 Tau) were obtained on 1981 February 7 and 8. The two fields overlap by approximately 50% in the $\sim 60' \times 60'$ useful region of the IPC field of view, and consequently 40 Pleiades stars fell into the overlap region. The characteristics of the two exposures are summarized in Table 1, while Table 2 lists those stars which are included in the field of view of the two exposures which are part of the cluster according to the Hertzsprung catalog (1947, hereafter Hz II). At the distance of the Pleiades, this catalogs completeness limit of apparent magnitude 14 correspond to spectral ty late K.

a) Analysis Procedures

The data have been analyzed by means of the revised *Einstein* IPC software (Harnden *et al.* 1984).[2] Images were searched for 3 σ fluctuations with respect to the local background in the energy band 0.2–3.5 keV. Vignetting, detection-cell extension, and shadowing by the IPC entrance aperture ribs were taken into account to give the effective count rate for each detected source together with its statistical error. With the detection threshold at 3 σ, approximately two of the sources are expected to be spurious. The positions of the detected X-ray sources were compared with the positions of all the stars (with $m_v < 14$) falling in the useful field of view. We have used as identification criterion the condition that the position of the X-ray source be within 1′ of the position of the optical star. This procedure gives a probability of chance identification with cluster members of less than 5×10^{-3}.

In addition to searching for X-ray sources in the field, we have also obtained count rates (corrected for instrumental effects as above) at the locations of all cluster stars in our catalog. Table 3 summarizes our results: We provide luminosities for all stars detected above the 3 σ level; call out all stars

for which the detection significance level lies between 2 σ and 3 σ, and give the corresponding luminosities; and provide 2 σ upper bounds for the remaining stars. Random fluctuations are expected to occur in $\sim 2\%$ of the trials in composing such a list; hence, about two false sources appear in the 2 σ portion of Table 3, for a total of perhaps four false sources in Table 3.[3] 232

[2] One of the important differences between this revised software and the former version is in the source-detection algorithm, which searches for fluctuations with respect to the *local* background rather than with respect to an *average* background. This ensures more reliable results for sources near the detection threshold, as well as in crowded fields.

[3] The results of a survey of the same region reported by Caillault and Helfand 1985 are not directly comparable to ours for the marginally detected sources, since they used the earlier "Rev O" *Einstein* software.

We have converted from count rates to X-ray luminosities using a conversion factor of 2.2×10^{-11} ergs count^{-1} cm^{-2}. This value was obtained by assuming a source temperature of $\sim 3 \times 10^6$ K and a hydrogen column density of 2.0×10^{20} cm^{-2}; the latter was computed according to Bohlin, Savage, and Drake (1978) using a reddening of $E(B-V) \approx 0.04$ (Crawford and Perry (1976). The total conversion factor for count rate to luminosity, assuming a common distance of 127 pc for all cluster members, is then 4.35×10^{31} ergs count^{-1}.

b) Results

We show a map of the region surveyed, giving the locations of both the Pleiades stars in the two fields and the detected sources. in Figure 1. The inferred X-ray luminosity along with its statistical uncertainty, or the 2 σ upper limit, are listed in Table 3 for all stars in our catalog, as explained above. The errors listed in Table 3 are the statistical errors. The estimated overall error in the X-ray luminosities is $\sim 40\%$–60%; it consists of statistical errors (ranging from 15% to 50%), systematic errors in instrument calibrations ($\leq 20\%$; Harnden *et al.* 1979), errors in the individual cluster member distance ($< 3\%$), and systematic errors in converting counts to flux due to the assumed hydrogen column density and source temperature ($\leq 20\%$).

We have detected a total of 21 distinct X-ray sources, associated with cluster members, 14 of which are significant at above the 3 σ level and 7 at above the 2 σ level. More specifically we have detected: one (1 + 0) out of eight B stars; one (1 + 0) out of 13 A stars; two (1 + 1) out of 10 F stars, 11 (11 + 0) out of 21 G stars; and six (1 + 5) out of 26 K stars in the Hz catalog (since the Hz catalog is not complete for apparent magnitudes greater than 14, this corresponds to an upper limit on the fraction of K stars detected).

Three additional X-ray sources detected at the 3 σ level do not correspond to any catalogued Pleiades star within a distance of 1′ from the detection-cell center. Two of these X-ray sources have been identified with field stars using the same identification criterion as discussed above; the remaining star may well correspond to an uncatalogued late K or M star.

Our results are summarized in graphical form in Figures 2–4. Figure 2 shows an H-R diagram of the cluster stars in the two fields of view for which count rates were obtained. The statistics of the breakdown into spectral types of the detected stars is given in Figure 3; Figure 4 summarizes the inferred X-ray luminosities and upper limits obtained in this survey. As can be seen from Figure 3, we have values fot the X-ray luminosity for more than 50% of the G stars in our sample; hence the median of the X-ray luminosity function for G stars in the Pleiades can be estimated from Figure 4 as the luminosity of the weakest X-ray source identified with a G star: L_x (median) $= 10^{29.5}$ ergs s^{-1}.

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III. DISCUSSION

In this section we discuss the conclusions which can be drawn from our survey, with particular attention to the dependence of the level of stellar X-ray emission on age.

a) Comparison with Other Surveys

It is particularly useful to compare the data presented here with the results of the *Einstein* Hyades survey (Stern *et al.* 1981). Only six stars (~7% of the stars from A to K) in the Hyades survey have been detected as X-ray sources with luminosities above the threshold for our Pleiades survey. Since the primary difference between these two open clusters is their age (the Pleiades being ~1/10 the age of the Hyades), it is natural to attribute this difference in X-ray luminosity to this age difference (or to stellar attributes which vary with stellar age); this point of view is also consistent with the expected decline of stellar activity with time for any given star.

More specifically, Stern *et al.* (1981) detected ~80% of the Hyades G dwarf stars, finding that the median X-ray luminosity for these stars (~$10^{29.1}$ ergs s^{-1}) is approximately 30 times the X-ray luminosity of the Sun (which is ~10 times older than the Hyades stars). Among the Hyades stars, three out of 13 G dwarfs have X-ray luminosity above of 2.5×10^{29} ergs s^{-1}; in comparison, we find that more than half of the Pleiades G dwarfs emit above this threshold. Since the Hz catagog is not complete for K stars, the comparison of detection statistics for K stars is not as meaningful as for the G stars. However, while Stern *et al.* did detect in X-rays only one out of the 18 K stars in their combined field of view at a level above 3×10^{29} ergs s^{-1}, we have detected six (or seven, if one assumes the source which has not been identified to be a K star) out of more than 26 K stars. Thus a clear decline in activity level (as measured by the stellar X-ray luminosity) with age is evident. This decline is illustrated in Figure 5, in which we plot the average detection threshold, the median, and the highest detection for X-ray observations of G spectral type T Tauri stars (Ku and Chanan 1979), Pleiades stars (this paper), Hyades stars (Stern *et al.* 1981), and local disk population members (Vaiana *et al.* 1981).

In order to quantify this behavior we have constructed maximum-likelihood luminosity functions (Avni *et al.* 1980; Schmitt 1984) for both the Pleiades and Hyades G dwarf stars. The Pleiades data used for these calculations are given in Table 3; the results of our computation for the Pleiades and Hyades are shown in Figure 6. We have applied a "bootstrap" calculation in order to compute the mean luminosities for the two clusters, including errors (Egron 1982; Schmitt 1984); we find that

$$\langle L_x \rangle_{\mathrm{Pleiades}} = 10^{29.6 \pm 0.1} \text{ ergs s}^{-1} ;$$
$$\langle L_x \rangle_{\mathrm{Hyades}} = 10^{29.1 \pm 0.1} \text{ ergs s}^{-1} .$$ [4]

4 We note, however, that the results reported by Stern *et al.* (1981) were obtained with the "Rev O" version of the *Einstein* data-analysis software, while our results for the Pleiades stellar cluster we obtained using the updated "Rev 1" software; for this reason, there might be small (~10%) discrepancies between our paper and theirs in the luminosity levels of stars.

We can therefore conclude that the Pleiades G stars have a significantly (>3 σ) higher level of X-ray emission than the Hyades G stars.

We have also compared the range of the X-ray luminosity for Pleiades stars in our survey that have $0.4 < B-V < 1.0$ with a similar sample of stars belonging to the Ursa Major cluster (Walter *et al.* 1984); specifically, the value of L_x for UMa members ranges between $10^{28.9}$ and $10^{29.6}$ ergs s^{-1}, while for Pleiades stars in our survey L_x ranges between $10^{29.3}$

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and $10^{30.3}$ ergs s^{-1}. Because the UMa cluster is older than the Pleiades cluster, this result is consistent with a trend of decreasing level of X-ray emission with stellar age. A more detailed comparison is not possible at this time because of the lack of upper bounds information for the UMa cluster.

In spite of the above reassuring evidence that stellar activity indeed declines as the stellar population ages, the Pleiades data also suggest that the sample picture in which the stellar-activity level of late-type stars is dominantly determined by the stellar-rotation rate, so that the age dependence is introduced by, for example, slow-down in the stellar spin rate, is not the entire story. In particular the absence of sources definitively identified with M dwarf stars is very puzzling. To see this, note that the median X-ray luminosity of Pleiades dG stars is ~ 50 times as large as the value found by Vaiana *et al.* (1981) for field dG stars. Then, if we assume that the X-ray luminosity function for the Pleiades dM stars is shifted by the same amount from that of the field stars, assume that the number of Pleiades M stars is ~ 10 times larger than that of G stars, (as is roughly the case for galactic-disc stellar-space densities; Allen 1976), and use the X-ray luminosity function of field dM stars derived by Rosner *et al.* (1981), we find that ~ 10 dM stars should have been seen above the threshold of our survey. Instead, we have observed only one source (X-3 in Table 3) which could possibly correspond to an uncatalogued M star; there are no other unidentified sources. We therefore conclude that the luminosity scaling with age must be spectral-type–dependent, as would occur if there were another stellar parameter (dependent upon spectral type) which figures in determining stellar activity level. The most plausible such parameter is the outer stellar convection depth; for example, Schmitt *et al.* (1985) have suggested that the activity level of dF stars is correlated with the Rossby number at the basis of the convection zone, and is thus related to a particular combination of rotation rate and convection zone depth (see also Noyes *et al.* 1984 for such evidence derived from Ca II data). We further note that the above argument derived from the (non)observation of dM stars is reenforced by a comparison of the X-ray luminosity functions of Pleiades dG and dK stars; using the nonparametric tests described by Schmitt (1984), we find that they are different at a significance level higher than 98%, with the dG star X-ray–luminosity function extending to higher values of L_x than that of the dK stars. This difference is quite remarkable in its own right and will be discussed further below.

b) X-ray Luminosity and Rotation

Only eight of the stars later than F7 (specifically: four K, one G, three F) in our sample have known values of projected equatorial velocities $v \sin i$; for 11 K stars, we have upper limits to $v \sin i$ and for two stars (one K, one G) we have lower limits to $v \sin i$. In particular, two K, two G, and one F stars detected as X-ray sources have projected equatorial velocity $v \sin i$ in excess of 45 km s^{-1}, while two K stars with $v \sin i > 50$ km s^{-1} were not detected (although their X-ray luminosity upper limits are quite high and hence not very constraining).

Figure 7 shows a log-log plot of X-ray luminosity and $v \sin i$ for stars of types F7 to K in our sample for which velocity measurements or upper/lower limits are available. As a comparison we have plotted the best fit for field stars obtained by Pallavicini *et al.* (1982); we note that the stars in the Pleiades have X-ray luminosities up to 2 orders of magnitude *lower* than RS CVn-type stars with comparable rotational velocity, or than the prediction of the Pallavicini *et al.* (1982) best fit. The RS CVn's are likely to have substantially different behavior in activity-rotation correlations from that of the present sample of stars because the former are close binaries; therefore we

have applied nonparametric maximum-likelihood linear regression analysis (including the upper bounds; Schmitt 1984) to our data shown in Figure 7 and to the data of Pallavicini *et al.* (1982), but excluding the RS CVn stars. We obtain $\log L_x \approx 27.5 + 1.5 \log v \sin i$ (solid line in Fig. 7), instead of the quadratic relationship between X-ray luminosity and projected equatorial velocity obtained by Pallavicini *et al.* (1982). Our regression function is, however, a poor fit to these data, suggesting that a single power law of the type applied here is not an adequate description of the data even in the RS CVn–excluded combined sample. 235

c) *The Rapidly-rotating but Relatively Inactive K Dwarfs*

Given the currently popular notion that stellar activity levels ought to correlate well with stellar rotation rates, it seems surprising that the Pleiades K dwarfs have systematically lower activity levels than the corresponding G dwarfs (shown most succinctly by the detection histogram in Fig. 3), because the dK stars in this cluster include a number of rapid rotators (cf. Stauffer *et al.* 1984). We believe that one can, however, account for this behavior. As suggested by the solar rotation evolution models of Endal and Sofia (1981), rapid evolution on the radiative track leads to spin-up of the entire star, which is followed by rapid spin-down (by magnetic braking) of the outer convective envelope. If, on average, the K stars in our sample correspond to the former evolutionary stage, while the G stars ()gain on average) correspond to the latter stage, then one would expect the rapidly rotating K dwarfs to have relatively modest rates of internal differential rotation at the convection zone–radiative core interface, whereas more slowly rotating G dwarfs would still have (at least just after the rapid envelope spin-down period) a rapidly spinning core and hence substantial differential rotation at this interface.

This scenario is supported by the fact that, at the nominal Pleiades age of $\sim 10^{7.7}$ yr, a solar-like star would have just reached the zero-age main sequence, as shown by Figure 5 of Endal and Sofia (1981). Such a star would already show a greater than threefold difference between its surface rotation rate and the (larger) radiative core rotation rate. In contrast, a lower mass K dwarf at the Pleiades age would not have reached this stage as yet, and the consequent maximum difference in rotation rate between the core and the surface would be less than twofold.

As has been recently suggested by Rosner (1980), Spiegel and Weiss (1980), and Golub *et al.* (1981), the presence of a shear near the base of an outer convective zone is highly favorable to a "shell dynamo" driven by a gradient in Ω at the convective envelope–radiative core boundary. Hence, one would expect on this model, at least qualitatively, that magnetic activity is most vigorous just at the point at which this differential rotation is maximized, thereby accounting for the observed difference in activity levels in the Pleiades G and K dwarfs. This scenario would also account for the paucity of X-ray sources associated with the dM stars in our Pleiades fields. This interpretation is not in contradiction with the observed high level of X-ray emission in T Tauri stars (e.g., Ku and Chanan 1979) both because the interior state of these stars is highly uncertain and because of the possible influence of primordial magnetic fields.

d) *A Stars*

The only A star which has been detected in X-rays in this survey (Hz II 1384) has an extremely high X-ray luminosity: $L_x \approx 1.3 \times 10^{30}$ ergs s^{-1}, i.e., three orders of magnitude higher than the value indicated as typical by Golub *et al.* (1983) in their survey of A stars detected by *Einstein*. As shown by

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Schmitt *et al.* (1984), A stars detected at peculiarly high values of X-ray luminosity are very likely in multiple systems in which the X-rays are dominantly emitted from an unseen late-type companion; however, Abt *et al.* (1965) have not found Hz II 1384 to be a spectroscopic binary. Furthermore, if we are to take the argument presented above seriously (and consider the relative dearth of detections of such stars), then any dK or later spectral-type companion ought not to be a vigorous X-ray source; instead, the X-ray luminosity of Hz II 1384 places it at the very upper end of the dG star luminosity function, and hence will above the emission levels observed and expected for later spectral type stars. Thus, although there is substantial observational motivation based on surveys of field dwarf A stars to place a strong upper bound on the possible contribution of the A star (in the hypothesized binary system) to the observed X-ray luminosity, the alternative (namely the presence of any lower-mass companion to this A dwarf which is responsible for the observed emission) appears to be problematic (as it would require a dG companion which is exceptionally bright in X-ray and which has escaped optical detection).

Given this difficulty, we would like to consider one remaining alternative explanation, which is even more speculative. A stars also go through a fully convective (well-mixed) stage during the descent to the main sequence; in this well-mixed regime, *large* radial gradients in rotation rate are unlikely. However, since the radial contraction which occurs during descent to the main sequence is nonhomologous, there must be a regime during which the star is (at least partially) convective and strongly differentially rotating. These circumstances are suitable for magnetic dynamo action, but continued dynamo action is not very plausible once the star has reached the main sequence (because convection ought to have ceased). Hence it may be that the observed activity is due to the dissipation of the magnetic fields produced during such an evanescent magnetically-active regime. This speculative suggestion seems to be consistent with the fact that the normal-field dA stars show no evidence for "activity" (Schmitt *et al.* 1985), but that dA stars known to be associated with strong surface magnetic fields (i.e., A_p stars such as ω Oph and α CVn) have been detected in X-rays, with $L_x \approx 10^{29}$ ergs s^{-1} (Golub *et al.* 1983).

e) *Variability*

We have searched for variability between the two IPC observations (i.e., on a time scale of ~ 1 day) for all the stars in the overlap region which were detected above the 3 σ level in both exposures. Our analysis detected variability (at a level of 3.3 σ) only in the X-ray flux of the star Hz II 303, which varied by a factor of ~ 3. No significant variability information could be obtained for the remaining stars in the overlap region.

IV. SUMMARY

We have analyzed the data obtained with two pointed observations of $1^\circ \times 1^\circ$ fields of the Pleiades region, have derived the maximum-likelihood X-ray luminosity functions for the Pleiades G and K stars in the cluster, and have shown that for the G stars, the Pleiades X-ray luminosity function is significantly brighter than the corresponding function for Hyades G dwarf. This finding indicates a dependence of X-ray luminosity on stellar age, which is confirmed by comparison of the same data with median X-ray luminosities of pre-main-sequence and local-disc-population dwarf G stars. Furthermore, although they are bright in X-rays, the X-ray luminosity of late-type Pleiades stars falls generally below the predictions of the $L_x \approx (v \sin i)^2$ relation of Pallavicini *et al.* (1981), for late-type main-sequence stars, indicating that such a simple relation between X-ray luminosity and rotational velocity for late-type

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stars is not an adequate description of the full data.

We have suggested that the significantly larger number of bright X-ray sources associated with G stars than with K stars, the lack of detections of M stars, and the relatively rapid rotation of the Pleiades K stars (Stauffer *et al.* 1984), can be explained in terms of the onset of internal differential rotation near the convective envelope–radiative core interface afte the spin-up phase during evolution to the main sequence. In this picture, the K stars are still spun-up, and have relatively little differential rotation, while the G stars have already started the spin-down by magnetic braking, thereby developing a gradient in angular velocity at the boundary between a fast rotating core and a slower convective envelope. Finally the detection of an A star in the cluster as a vigorous X-ray source cannot be readily accounted for by invoking either intrinsic emission along the lines of the "solar analogy," or an unresolved low-mass, active companion, raising the question whether the observed emission is the "aftermath" of an earlier epoch of magnetic dynamo activity during the descent of the (convecting) progenitor star to the main sequence.

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TABLE 1

CHARACTERISTICS OF THE OBSERVATIONS

	I-5457	I-5458
Center coordinates (α, δ)	$3^h41^m54^s.1$ $23°57'27''.8$	$3^h42^m50^s.8$ $24°12'46''.9$
Start time (JD)	2142.8131	2143.9195
Effective exposure (s)	2931.0	4734.4
Cluster stars ($m_v < 14$)	57	61
Limiting sensitivity	$\sim 2.8 \times 10^{29}$ ergs s^{-1}	$\sim 2.3 \times 10^{29}$ ergs s^{-1}

TABLE 2

Pleiades Stars in this Survey

Hz II	R.A. (1950)	Decl. (1950)	m_v	Ref.	$B-V$	Sp.[a]	Ref.	V_r[b]	Ref.	P[c]	Notes
120	$3^h40^m34^s.1$	23°31′03″	10.79	1	0.70	F6		...		...	
158[d]	3 40 44.5	24 13 06	8.23	1	0.25	A7	2	70	3	...	
193[d]	3 40 52.2	24 05 29	11.29	1	0.81	G7		...		0.97	
232	3 41 01.3	24 24 04	8.06	1	0.20	A5	2	20	3	...	HD 23194
233	3 41 00.7	23 43 37	9.66	1	0.52	F7		80	3	...	
253	3 41 04.6	24 20 54	10.66	1	0.68	G1	4	...		...	
263[d]	3 41 06.2	24 07 10	11.54	1	0.88	G8	4	...		0.98	
298[d]	3 41 14.4	23 52 34	10.86	1	0.88	G + K		...		...	e
299[d]	3 41 14.7	23 52 30									
303[d]	3 41 16.2	23 56 47	10.48	1	0.89	G9		...		...	
314	3 41 20.8	24 38 26	10.56	1	0.64	G1	4	...		...	
320	3 41 21.2	24 37 02	11.04	1	0.88	G5	4	...		...	
324	3 41 22.6	24 36 46	13.00	5	1.07	K2		90		...	
335[d]	3 41 24.6	23 54 46	13.76	5	1.28	K5	6	...		0.56	f
338	3 41 25.1	23 58 37	9.07	1	0.46	F2	2	< 40	3	...	
344[d]	3 41 26.9	24 14 21	8.17	1	0.27	A8	2	200	3	...	
345[d]	3 41 27.2	24 26 03	11.65	5	0.85	G8	4	...		0.99	
357	3 41 29.4	24 00 58	13.32	7	1.19	K6	6	< 10		0.99	f
405	3 41 41.5	24 39 47	9.83	1	0.54	F9	2	15	8	...	
430[d]	3 41 45.3	24 04 33	11.45	5	0.85	G8	4	...		0.99	
447[d]	3 41 49.5	24 08 04	5.46	1	−0.04	B7 IV	2	260	3	...	16 Tau
468[d]	3 41 54.0	23 57 29	3.71	1	−0.11	B6 III	2	220	3	...	17 Tau
476[d]	3 41 55.6	23 45 58	10.81	1	0.80	G1	4	...		...	HD 23302
489[d]	3 41 57.6	24 16 39	10.36	1	0.63	G0	2, 4	...		...	
522[d]	3 42 05.1	23 41 05	11.97	5	0.92	K2	9	...		0.99	
530	3 42 07.2	23 32 52	8.95	1	0.39	F3		< 40	3	...	
531[d]	3 42 07.9	24 06 31	8.58	1	0.31	Am?	2	75	3	...	
541	3 42 10.4	24 41 03	5.65	1	−0.07	B8	2	245	3	...	HD 23324
554	3 42 12.9	24 25 53	14.09	9	0.92	K5	9	...		0.94	
563	3 42 13.5	24 18 45	4.31	1	−0.11	B6	2	135	3	...	19 Tau
625	3 42 23.1	23 34 23	12.57	1	1.10	K3		> 50		0.96	g
652	3 42 27.7	23 52 50	8.04	1	0.21	A3	2	235	3	...	
676	3 42 31.4	23 36 21	13.71	5	1.31	K3.5	6	< 10		0.99	f
686[d]	3 42 34.2	24 08 56	13.62	1	1.04	K2		150		0.99	f, g
697[d]	3 42 35.5	24 18 32	8.60	1	0.35	A9	2	75	3	...	
708[d]	3 42 36.9	23 55 44	10.13	1	0.62	G0	4	70	8	...	
717[d]	3 42 39.0	24 10 53	7.18	1	0.16	A1	2	15	3	...	HD 23387
727	3 42 41.1	24 28 23	9.70	1	0.55	F9	2	45	8	...	
738	3 42 41.3	23 35 60	12.26	1	1.16	G5	10	> 60		0.93	
745[d]	3 42 42.7	24 08 03	9.45	1	0.52	F5	2	65	8	...	
746[d]	3 42 42.9	24 16 38	11.27	1	0.92	G5	4	...		0.99	
761[d]	3 42 45.7	24 03 58	10.55	1	0.67	G1	4	...		...	
785[d]	3 42 50.8	24 12 49	3.88	1	−0.07	B7 III	2	40	3	...	20 Tau
793[d]	3 42 50.7	23 41 56	14.305	5	1.40	K8		< 10		0.96	f
799[d]	3 42 52.2	23 43 12	13.71	5	1.31	K3	10	< 10		0.96	
804	3 42 53.2	23 53 05	7.85	1	0.20	A2	2	170	3	...	
817	3 42 55.4	24 24 02	5.76	1	−0.04	B8	2	220	3	...	21 Tau
859	3 43 03.9	24 22 26	6.43	1	−0.02	B9	2	250	3	...	22 Tau
870	3 43 04.7	23 35 00	12.72	1	1.24	K5		...		0.93	
879[d]	3 43 07.4	24 24 49	12.82	5	1.08	K2		< 10		0.96	e, g
883[d]	3 43 07.8	24 24 33	13.05	5	1.15	K4		...		0.99	e, f

TABLE 2—*Continued*

Hz II	R.A. (1950)	Decl. (1950)	m_v	Ref.	$B-V$	Sp[a]	Ref.	V_r[b]	Ref.	P[c]	Notes
885	$3^h43^m08^s.3$	24°42′47″	12.05	1	1.01	K3	4	< 10		0.97	
916[d]	3 43 12.6	24 28 07	11.71	1	0.87	G8	4	...		0.99	
956[d]	3 43 17.3	24 02 10	7.96	1	0.32	F0		150	3	...	HD 23479
974	3 43 21.1	24 37 55	13.86	5	1.32	K7	9	...		0.95	
980	3 43 21.1	23 47 41	4.18	1	−0.06	B6 IV	2	275	3	...	23 Tau
996[d]	3 43 23.5	24 25 00	10.42	1	0.64	G1	4	...		...	
1028[d]	3 43 28.5	24 06 06	7.35	1	0.10	A2	2	110	3	...	
1032[d]	3 43 29.4	24 16 50	11.34	1	0.86	G8	4	...		0.99	
1061[d]	3 43 32.5	23 57 49	14.28	5	1.42	K5	10	< 10		0.95	f
1094[d]	3 43 37.5	23 48 49	14.02	1	1.40	K8		...		0.91	e, f
1100[d]	3 43 38.4	24 11 24	12.16	1	1.15	K3	4	< 10		0.92	f
1110[d]	3 43 39.8	24 22 01	13.41	9	1.23	K6.5	6	...		0.99	
1117	3 43 39.5	23 38 04	10.20	1	0.73	G6	2	...		...	
1122	3 43 40.7	23 56 60	9.29	1	0.46	F4	2	28	10	...	
1124[d]	3 43 40.8	23 52 35	12.12	1	0.92	K0	4	< 10		0.97	g
1207	3 43 55.4	24 38 36	10.47	1	0.62	G1	4	...		...	
1266	3 44 04.1	24 40 01	8,28	1	0.36	F2		95	3	...	
1280[d]	3 44 04.9	24 00 25	14.55	5	1.37	K7	10	...		0.97	
1284[d]	3 44 05.7	23 50 32	8.37	1	0.30	A9	2	100	3	...	
1298	3 44 08.6	23 33 44	12.18	1	1.02	K2		10		0.98	
1355	3 44 19.6	23 53 03	14.07	7	1.40	K5	6	< 10		0.77	
1380	3 44 22.6	23 39 02	6.99	1	0.03	A1	2	235	3	...	e
1384	3 44 24.8	24 26 09	7.66	1	0.21	A4	2	215	3	...	
1431	3 44 30.6	24 08 09	6.81	1	0.06	A40	2	40	3	...	
1454	3 44 34.3	24 31 54	12.82	1	1.14	K5	10	< 10		0.97	
1514	3 44 34.4	24 12 44	10.48	1	0.64	G1		...		...	
1516	3 44 41.4	24 08 58	13.87	5	1.27	K6		...		0.99	f
1531	3 44 42.9	23 49 11	13.41	8	1.22	K5		50		0.94	g

[a] Spectral type computed according to Allen 1976 from the quoted $B-V$ values, unless otherwise noted.
[b] Equatorial velocity projected along the line of sight (km s^{-1}), from Stauffer *et al.* 1984, except when otherwise noted.
[c] Probability of cluster's membership according to Jones 1973.
[d] Star present in the overlap region of the two exposures.
[e] Double system: data from Binnendijk 1946, except when otherwise noted.
[f] Flare star; data from Binnendijk 1946, except when otherwise noted.
[g] Photometric periodic variable (Van Leewen and Alphenaar 1982, Alphenaar and Van Leewen 1981).

REFERENCES.—(1) Johnson and Mitchell 1958. (2) Mendoza 1956. (3) Anderson, Stoeckly, and Kraft 1966. (4) Wilson 1963. (5) Landolt 1979. (6) Kraft and Greenstein 1969. (7) Stauffer 1980, Stauffer *et al.* 1984. (8) Kraft 1967. (9) Jones 1973. (10) Herbig 1962.

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TABLE 3

X-Ray Luminosities of Stars in the Survey
(10^{29} ergs s^{-1})

Hz II	Spectral type	I 5458	I 5457
120	F6	...	<7.8
158	A7	<2.7	<4.6
193	G7	6.3 ± 1.6	3.5 ± 1.2
232	A5	...	<3.2
233	F7	...	<2.0
253	G1	...	22.4 ± 3.2
263	G8	4.6 ± 1.7[a]	5.4 ± 1.6
298	G + K	2.9 ± 1.4[a]	4.8 ± 1.4
299	G + K		
303	G9	14.4 ± 2.3	5.2 ± 1.6
314	G1	<8.7	...
320	G5	8.8 ± 2.6	...
324	K2	<8.7	...
335	K5	<6.5	<2.6
338	F2	...	<2.9
344	A8	<1.7	<2.8
345	G8	12.7 ± 1.9	10.9 ± 2.7
357	K6	...	<3.0
405	F9	<4.4	...
430	G8	<1.6	<2.1
447	B7 IV	<1.4	<1.9
468	B6 III	<1.7	<1.5
476	G1	<2.7	<2.1
489	G0	<1.8	<5.2
522	K2	<2.2	<2.5
530	F3	...	<2.6
531	Am?	<1.4	<1.9
541	B8	<2.9	...
554	K5	2.0 ± 0.9[a]	<3.1
563	B6	<2.1	...
625	K3	...	5.9 ± 1.7
652	A3	...	<1.9
676	K3.5	...	<3.6
686	K2	<2.0	3.1 ± 1.5[a]
697	A9	<1.6	<3.1
708	G0	4.7 ± 1.2	2.9 ± 1.2[a]
717	A1	<1.6	<2.0
727	F9	9.1 ± 1.5	...
738	G5	...	6.5 ± 2.0
745	F5	<1.9	3.4 ± 1.5[a]
746	G5	<1.4	<3.1
761	G1	3.3 ± 1.0	<2.7
785	B7 III	<1.6	<2.4
793	K8	<3.8	<6.2
799	K3	2.9 ± 1.5[a]	<3.7
804	A2	...	<1.9
817	B8	<1.8	...
859	B9	<1.6	...
870	K5	...	<2.5
879	K2	<1.8	<6.0
883	K4	<1.8	<6.4

TABLE 3—*Continued*

Hz II	Spectral type	I 5458	I 5457
885	K3	<2.4	...
916	G8	<1.5	<3.9
956	F0	<4.1	<8.3
974	K7	<2.2	...
980	B6 IV	4.2 ± 1.6[a]	...
996	G1	<2.1	<4.8
1028	A2	<1.4	<2.4
1032	G8	8.2 ± 1.4	6.9 ± 2.4[a]
1061	K5	<2.2	<3.0
1094	K8	<2.8	<3.5
1100	K3	2.8 ± 1.0[a]	3.7 ± 1.7[a]
1110	K6.5	<1.6	<5.4
1117	G6	...	<12.8
1122	F4	...	<3.5
1124	K0	<3.2	4.3 ± 1.8[a]
1207	G1	<8.4	...
1266	F2	<4.1	...
1280	K7	<2.1	<4.3
1284	A9	<1.8	<3.4
1298	K2	...	<8.0
1355	K5	<3.1	...
1380	A1	...	<6.8
1384	A4	13.1 ± 2.1	...
1431	A0	<2.0	...
1454	K5	<2.2	...
1514	G1	<5.0	...
1516	K6	<2.6	...
1531	K5	<5.8	...
X-1[b]	...	4.1 ± 1.0	...
(938/939)	K		
X-2[b]	...	2.8 ± 0.98	...
(1053)			
X-3[b]	...	5.0 ± 1.5	...

[a] Count rate determined at the star location, 2 σ above local background (see text).

[b] The X-ray sources not associated with cluster members are at:

$$\alpha_1 = 3^h43^m15^s \qquad \delta_1 = 24°01'49''$$
$$\alpha_2 = 3\ 43\ 33 \qquad \delta_2 = 24\ 04\ 08$$
$$\alpha_3 = 3\ 44\ 34 \qquad \delta_3 = 24\ 13\ 08$$

X-1 is within 1′ of the FO cluster member Hz II 956, but the source centroid is also near the field binary system. Hz II 938-939. This system is nearer than the Pleiades and contains a K star, so we tentatively identify X-1 with Hz II 938-939. Hz II 1053 is not a cluster member.

REFERENCES

Abt, H. A., Barnes, R. C., Biggs, E. S., and Osmer, P. S. 1965, *Ap. J.*, **142**, 1604.
Allen, C. W. 1976, *Astrophysical Quantities* (London: Athlone Press).
Alphenaar, P., and van Leeuwen, F. 1981, *Inf. Bull. Var. Stars*, No. 1957.
Anderson, C. N., Stoeckly, R., and Kraft, R. P. 1966, *Ap. J.*, **143**, 299.
Avni, Y., Soltan, A., Tananbaum, H., and Zamorani, G. 1980, *Ap. J.*, **238**, 800.
Bohlin, R., Savage, B. D., and Drake, J. F. 1978, *Ap. J.*, **224**, 132.
Binnendijk, K. L. 1946, *Ann. Leiden Obs.*, **19**, Part 2.
Caillault, J. P., and Helfand, D. J., 1985, *Ap. J.*, **289**, 000.
Crawford, D. L., and Perry, C. L. 1976, *A.J.*, **81**, 419.
Efron, B. 1982, *The Jackknife, the Bootstrap and Other Resampling Plans* (Philadelphia: SIAM), No. 38.
Endal, A. S., and Sofia, S. *Ap. J.*, **244**, 625.
Feigelson, H. C., and De Campli, W. M. 1981, *Ap. J. (Letters)*, **243**, L89.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Golub, L., Rosner, R., Vaiana, G. S., and Weiss, N. O. 1981, *Ap. J.*, **243**, 309.
Golub, L., Harnden, F. R., Jr., Maxson, C. W., Rosner, R., Vaiana, G. S., Cash, W., and Snow, T. P. 1983, *Ap. J.*, **271**, 264.
Gorenstein, P., Harnden, F. R., Jr. and Fabricant, D. G. 1981, *IEEE Trans. Nucl. Sci.*, NS-28, 869.
Harnden, F. R., Jr., Fabricant, D. G., Harris, D. E., and Schwarz, J. 1984, *Smithsonian Ap. Obs. Spec. Rept.*, No. 393.
Harnden, F. R., Jr., *et al.* 1979, *Ap. J. (Letters)*, **234**, L51.
Herbig, G. H. 1962, *Ap. J.*, **135**, 736.
Hertzsprung, E. 1947, *Ann. Leiden Obs.*, **19**, Part 1A (Hz II).
Johnson, H. L., and Mitchell, R. I. 1958, *Ap. J.*, **128**, 3.
Jones, B. F. 1973, *Ap. J. Suppl.*, **9**, 313.
Kraft, R. P. 1967, *Ap. J.*, **150**, 552.
Kraft, R. P., and Greenstein, J. L. 1969, in *Low Luminosity Stars*, ed. S. S. Kumar (New York: Gordon and Breach), p. 65.
Ku, W. H., and Chanan, G. A. 1979, *Ap. J. (Letters)*, **234**, L59.
Landolt, A. U. 1979, *Ap. J.*, **231**, 468.
Micela, G., Sciortino, S., Serio, S., Vaiana, G. S., Golub, L., Harnden, F. R., Jr., and Rosner, R. 1983, in *Observational Tests of the Stellar Evolution Theory*, ed. H. Maeder and A. Renzini (Dordrecht: Reidel), p. 101.
Micela, G., Sciortino, S., and Serio, S. 1984, *Proc. "X-Ray Astronomy 84" Symp.* (Bologna), in press.
Mendoza, V. E. E. 1956, *Ap. J.*, **123**, 54.
Montmerle, T., Koch-Miramond, L., Falgarone, E., and Grindlay, J. E. 1983, *Ap. J.*, **269**, 182.
Noyes, R., W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., and Vaughan, A. H. 1984, *Ap. J.*, **279**, 763.
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T., and Linsky, J. L. 1981, *Ap. J.*, **248**, 279.
Pallavicini, R., Golub, L., Rosner, R., and Vaiana, G. S. 1982, in *2d Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. M. S. Giampapa and L. Golub (Smithsonian Astrophysical Observatory Special Report No. 392), p. 77.
Robinson, R., and Kraft, R. P. 1974, *A.J.*, **79**, 698.
Rosner, R., 1980, in *Cool Stars, Stellar Systems and the Sun*, ed. A. K. Dupree (Smithsonian Astrophysical Observatory Special Report No. 389), p. 79.
Rosner, R., Avni, Y., Bookbinder, J., Giacconi, R., Golub, L., Harnden, F. R., Jr., Maxson, C. W., Topka, K., and Vaiana, G. S. 1981, *Ap. J. (Letters)*, **249**, L5.
Schmitt, J. H. M. M., 1984, *Ap. J.*, ????
Schmitt, J. H. M. M., Golub, L., Harnden, F. R., Jr., Maxson, C. W., Rosner, R., and Vaiana, G. S. 1985, *Ap. J.*, **290**, 000.
Serio, S., 1984, in *Proc. "X-Ray Astronomy 84" Symp.* (Bologna), in press.
Spiegel, E. A., and Weiss, N. O. 1980, *Nature*, **287**, 616.
Stauffer, J. R., 1980, *A.J.*, **85**, 1341.
Stauffer, J. R., Hartmann, L., Soderblom, D. R., and Burnham, N. 1984, *Ap. J.*, **280**, 189.
Stern, R. A., Zolcinski, M. C., Antiochos, S. C., and Underwood, J. M. 1981, *Ap. J.*, **249**, 647.
Topka, K. P., *et al.* 1982, *Ap. J.*, **259**, 677.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **245**, 163.
van Leeuwen, F., and Alphenaar, P. 1982, *ESO Messenger*, **28**, 15.
Walter, F. M. 1981, *Ap. J.*, **245**, 677.
Walter, F. M., Linsky, J. L., Simon, T., Golub, L., and Vaiana, G. S. 1984, *Ap. J.*, **281**, 815.
Wilson, O. C. 1963, *Ap. J.*, **138**, 832.

FIG. 1.—Schematic map of the two IPC fields, showing the location of the surveyed Pleiades stars (*points*) and the X-ray sources detected (*circles*). The crosses indicate three X-ray sources not identified with cluster members. Noncluster stars are not shown.

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FIG. 2.—H-R diagram for the Pleiades stars in the two IPC fields. X's represent X-ray detections at a level of significance above 2 σ.

FIG. 3.—X-ray detection statistics for the Pleiades stars; we show both the fraction of the total number of stars in each spectral-type range which were detected and the number of individual sources observed in each spectral type (given as numbers at the bottom of each bin). Note that the detection fraction shown for the K stars is an upper limit because the Hz II optical catalogue is complete only to $m_V = 14$.

FIG. 4.—Summary of X-ray detections, represented by diamonds (2 σ level) and octagons (3 σ level). For stars observed in both IPC fields, the detections (or detection and constraining upper limit) are joined by a solid line.

FIG. 5.—Dependence of the median X-ray luminosity on age for different samples of G stars. Bars are located at the values of the median X-ray luminosity; their length represents the uncertainty in age determination in each group. The range of observed luminosities is indicated by ● (the lower ● is always fixed by the detection threshold in each group). (*a*) Pre-main-sequence G stars (Ku and Chanan 1979; Feigelson and De Campli, 1981); (*b*) Main-sequence G stars in the Pleiades (present survey); (*c*) Main-sequence G stars in the Hyades (Stern *et al.* 1981); (*d*) Local disk popula ion dwarf G stars (Vaiana *et al.* 1981; Topka *et al.* 1982; Rosner *et al.* 1981).

FIG. 6.—Maximum-likelihood integral X-ray luminosity functions of Pleiades (*solid line*) and Hyades (*dashed line*) G dwarfs.

FIG. 7.—Log of the X-ray luminosity vs. 5he log of the projected equatorial rotational velocity for the Pleiades stars later than F7 for which values of, or bounds on, these velocity are known. Our data are shown as octagons when we have measurements for both the values of L_x and $v \sin i$. When only one of the two quantities has been measured (so that we know an upper or lower limit for the other quantity), the corresponding limit is indicated by an arrow pointing in the appropriate direction; when we have only upper/lower limit information on both variables, this is indicated by double arrows. For comparison, we also plot (*dashed line*) the best fit of Pallavicini *et al.* (1981) including normal dwarf stars, RS CVn's, T Tauri stars, and Hyades stars. The solid line represents the linear regression (including upper limits, Schmitt 1984) to all data without including the RS CVn's: $\log L_x \approx 27.47 + 1.48 \log v \sin i$.

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Numerical Simulations of Flare Evolution (Contribution to Report of Team E of the SMM workshop)

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ABSTRACT

We report on the numerical simulation of two well observed SMM flares by means of a hydrodynamical code for plasma confined in a magnetic flux tube. The parameters of the model loops are obtained from the SMM and ground based observations and the only free parameters in the models are relative to the spatial and temporal distribution of the impulsive energy source. We generally find good agreement between the simulated and the observed XRP light curves, and we obtain extimates for the total energy input to the two flares.

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1. Introduction

As part of the team E effort in the SMM workshop, we have used the Palermo - Harvard Numerical Hydro Model (Peres et al. 1982, Pallavicini et al. 1983, Peres et al. 1983; see also the chapter on numerical modelling in this book) as a diagnostic tool to gain insights into the energetics of the gradual phase in compact loop flares. In particular, we have used the model to fit the light curves observed with the X-Ray Polychromator on SMM. Since this fitting imposes constraints on the characteristics of the energy input, we can use the model to evaluate various aspects of the flare energetics such as, for instance, the overall energy budget.

In our approach to the flare modelling, we use the FeXXV light curve, provided by the BCS and the FCS instruments, as a diagnostic tool to ascertain the approximate duration and intensity of the impulsive heating term. Our previous work (Pallavicini et al. 1983) has, in fact, shown that the computed FeXXV line emission starts to decline as soon as the heating term is effectively switched off, almost independent of the localization of the heat source in the loop. This, however, does not exclude the possibility of a rapidly-decaying heating component and, in fact, the best agreement of the model predictions and the observations has been obtained so far by taking into account an exponentially-decaying heating term in the decay phase of the FeXXV line.

To gain information about the localization and the spatial distribution of the heating from the SMM images is a more difficult task. In particular, while a brightening in a pixel (for instance overlaying one of the loop footpoints) is clear evidence for enhanced emission, it is not necessarily evidence for the localization of the heating in that region, unless the data are resolved in times shorter than the conduction travel time. Heat might, in fact, have been deposited elsewhere in the magnetic loop and brought there by thermal conduction. For example, the conduction times for the May 7 flare and the November 12 flares, which will be discussed below, are less than 5 seconds and 20 seconds respectively which should be compared with FCS observations with a time resolution of, respectively, 150 seconds and 70 seconds. Moreover, the coronal part of the loop at the beginning of a flare has a relatively low emission measure, and therefore will not emit significantly in high temperature lines before the evaporation has filled the loop with large amounts of material.

Both the short heat conduction time and the low initial emission measure in corona conspire therefore to give low significance to inferences on heating

localizations based on simplified image analysis. More reliable information can be obtained only from images taken with spatial and temporal resolution high enough to ascertain the loop geometry and to resolve the first few seconds.

A detailed knowledge of geometry and preflare conditions is crucial for a realistic flare modelling (e.g., Pallavicini et al. 1983). Comparison with observations has been made for the flares of May 7, 1980 at ~ 15:00 U.T. and November 12, 1980 at ~ 17:00 U.T. These flares have been chosen because detailed data are available both on their geometry and preflare conditions, and because they appear to be compact loop flares (our model does not consider field line disruption and therefore can be applied only to compact loop flares). For both flares we shall present a short summary of the observational data and the results of the comparison with model calculations. The primary observations were provided by the XRP experiment on SMM (Acton et al. 1980). Hα and magnetic data were also used to examine the magnetic field structure.

We have assumed, for simplicity and as a first step in our analysis, symmetric transient heating localized at the top of the loop, with a heat deposition having a gaussian distribution along the field line coordinate. This might be a coarse approximation in the case of the May 7 flare because Hα observations (Acton et al. 1982) indicate that the two footpoints had different intensities at the chromospheric level, which might be construed as evidence of asymmetric heating in the loop. The amount of impulsive energy deposited in the loop was chosen so as to reproduce the observed maximum temperature and the FeXXV line maximum flux, while the time evolution of the heating was chosen in such a way as to reproduce the FeXXV line light curve. In order to achieve high flexibility in changing the model parameters, we have prescribed the impulsive heating as a separable function of space coordinate and time as

$$H(s,t) = H_0 \times f(t) \times g(s) \qquad [1]$$

$$g(s) = \exp\left\{\frac{-[(s-s_0)]^2}{2 \times \sigma^2}\right\} \qquad [2]$$

2. The May 7 Flare

2.1 Observations

The flare on May 7, 1980 at 15:00 U.T. was a compact, short-lived event of low total intensity, but a quite energetic one, as indicated by the substantial emission in high temperature lines (CaXIX and FeXXV). FCS observations show that it was confined within a single 15" x 15" pixel. The light curves were observed by the FCS throughout its entire evolution with low temporal resolution (2.5 minutes; see figure 1 for the complete set of FCS observations). An extensive analysis of this event, based on simultaneous SMM and Hα observations has been given by Acton et al. (1982), and the X-ray observations have also been discussed by Simnett (1983).

As shown by the comparison of Hα and soft X-ray observations, the flare consisted of a single compact loop of semilength $L \cong 5.7 \times 10^8$ cm. The cross section of the loop has been derived from the size of the Hα footpoints and is A= 8.8 x

10^{16} cm^2, which implies an aspect ratio (loop diameter/loop length) α= 0.34. Preflare coronal conditions have been determined using the FCS fluxes observed in the same pixel before the onset of the flare. A preflare temperature of T= (2.5 ± 0.5) x 10^6 K has been derived from the ratio of the resonance lines of NeIX and MgXI.

The initial pressure and density have been inferred from the loop temperature and length using the scaling law of Rosner, Tucker and Vaiana (1978). The derived initial pressure was p_o ~ 10 dyne cm^{-2}, implying a coronal density of n= 1.4 x 10^{10} cm^{-3} before the flare. This density is near the upper bound of the range of typical densities observed in active region loops (10^9 - 10^{10} cm^{-3}) yet it is consistent with the accepted scenario of coronal loops which assigns high density to small and compact loops and low density to long and extended ones. Comparison of these initial values with pressure and density derived from the <u>total</u> emission measure in the same FCS pixel before the flare shows that the latter ones are substantially higher than those predicted on the basis of the scaling law (p_o = 49 dynes/cm^{-2}, n_o= 7 x 10^{10} cm^{-3}); this suggests that the flaring loop was not the main contributor to the total emission from this 15" x 15" FCS pixel during the preflare stage. This result is not unusual and has been found in many flares observed with the FCS; in particular, it has also been observed in the Nov 12 flare discussed below.

2.2 Simulations

The parameters and the time evolution function used to fit the observations were

$$H_o = 175 \text{ ergs cm}^{-3} \text{ sec}^{-1}$$
$$s_o = 5.7 \times 10^8 \text{ cm.}$$
$$\sigma = 10^8 \text{ cm.}$$

$$f(t) = \begin{cases} t/150 & 0 < t < 150 \text{ seconds} \\ \exp[(150 - t)/\tau] & t > 150 \text{ seconds} \end{cases}$$

In a first attempt, the decay time τ was assumed to be zero (i.e., an instantaneous switch-off of the heating). Although our calculation has been performed with the transient heating localized at the top of the model loop, we wish to emphasize that this choice is not the only possible one. Previous numerical code results (Pallavicini <u>et al.</u> 1983) have shown little difference between top and bottom heated flares, at least as far as predictions of light curves in the various spectral lines are concerned (see however Peres <u>et al.</u> 1983 for other possible diagnostics). In any case since the May 7 flare was imaged in only a single resolution element of the FCS, the data cannot give any information about the heat source localization.

As shown in figure 2, the above set of parameters allows us to fit quite well the FeXXV and CaXIX BCS light curves during the rise phase of the flare. Owing to the low temporal resolution of the FCS observations of this flare (2.5 minutes), the FCS light curves cannot be used to further constrain the fitting of the rise phase. It is apparent that our first choice of the decay time (τ= 0) does not fit the FeXXV and CaXIX observations in that the predicted light curves decay faster than observed. Figure 3 shows an analogous disagreement between predicted and observed OVIII and Ne IX light curves in the decay phase. Our next attempt has been to assume a non-zero decay time for the heating function, all the other parameters remaining the same. Figure 4 shows our results for τ= 30 sec.

The large increase in density and in temperature in the course of a flare generally causes a decrease of all the characteristic time scales for a given loop model (for example, the radiative cooling time and the conduction cooling time of the corona, the sound travel time across the space grid, etc.) and therefore imposes small computational time steps. In the case of the May 7 flare this requirement was particularly severe, expecially during the early decay phase. This difficulty and the practical limitations of the available computer time have induced us to model only the first 20 seconds of the decay phase. It is, however, already evident that the heating decay time is still too short, and that a decay time of τ= 60 seconds would bring our predictions much closer to the observations.

Among the energy terms considered in our model i.e., thermal, gravitational and kinetic, the thermal energy is, as expected, the dominant component by, tipically, an order of magnitude throughout the flare evolution. Figure 5 shows the evolution of the total thermal energy content of the flare during the rise phase.

According to our model, the total energy deposited in the flare during the rise phase is 2.9×10^{29} ergs. Allowing for an additional energy deposition during the decay phase with an exponential decay time of 60 secs., one obtains a total energy input of 5×10^{29} ergs.

Some uncertainty in the total energy input is related to our lack of knowledge of the site of energy deposition. The energy input necessary for a fit of the FCS lines can, in fact, be higher by a factor of, at most, two in the case of energy deposition localized near the loop footpoints.

3. The November 12 flare

3.1 Observations

The flare of November 12, 1980 at 17:00 U.T. was substantially different from the May 7 event in that it had a larger spatial extent (covering at least three 15"x15" FCS pixels) and a somewhat lower density and pressure in the preflare state. The light curves in soft X-ray lines appear to be typical of most flares observed with the FCS. Since the minimum integration time step required during the decay phase was larger than in the case of the May 7 event, the simulations could be carried further than in the former case.

An extensive analysis of this event, based on all the available ground based and SMM observations is being carried on as part of the UK-SMM workshop (MacNeice et al. 1984). In this section we will refer only to XRP and Hα observations as more pertinent to the gradual phase.

The magnetic field configuration has been inferred by comparing FCS rasters - obtained at 70 secs interval - with simultaneous Hα images provided by the SOON network. The Hα images show loop footpoints on opposite sides of the magnetic neutral line, suggesting a loop or a family of loops arching between the two main Hα emitting regions. Soft X-Ray images taken by FCS show an elongated arc-shaped structure, brighter at both ends in the low temperature lines NeIX and MgXI during the early phase of the flare. At the same time, high temperature lines (mainly SXV and FeXXV) appear to be stronger at what appears to be the top of a loop. The low temperature soft X-Ray regions coincide, within the FCS spatial resolution (15") and the alignment accuracy (10"), with the Hα footpoints, while the FeXXV high temperature region is located in between the Hα/NeIX footpoints, showing evidence of enhanced brightening at the loop apex. This fact supports a working hypothesis of heating localized at the loop apex. Diagnostic tecniques applied to BCS lines show that the coronal portion of the loop was initially at a temperature of 2×10^7

K and decayed rapidly during the flare evolution.

From the combined analysis of the Hα and FCS observations we find that the main flaring structure was a loop with semilength $L \cong 2. \times 10^9$ cm and cross-sectional area $A = 2.5 \times 10^{17}$ cm^2. The aspect ratio is therefore $\alpha = 0.14$. The complex magnetic structure of the region and the spatial distribution of the observed Hα emission also suggests that other smaller loops were also probably involved in the flare, but that they were not dominant throughout its evolution.

Preflare conditions were determined using the same method as for the May 7 flare. The preflare temperature was $T = 3.0 \pm 0.5 \times 10^6$ K and the preflare pressure derived on the basis of the scaling laws of Rosner, Tucker and Vaiana (1978) was $p_o = 6$ dynes cm^{-2}, corresponding to an average density $n_o = 7 \times 10^9$ cm^{-3} in the coronal portion of the loop. The density and the pressure derived from the total emission measure in the same FCS pixels during the preflare phase were substantially larger than (and not consistent with) the same scaling laws, again suggesting that the flaring loop was not the dominant one during the preflare phase and that the area imaged into FCS pixels was filled with structures other than the loop which later flared.

The impulsive heating localization and distribution can be inferred from FCS observations which show FeXXV emission to be confined within one central 15"x15" pixel, which suggests (altough this cannot be taken as proof) that the transient heating was localized at the loop apex; the size of the pixel where the FeXXV emission was recorded at the beginning suggests an upper limit for the dimension of the directly heated region and therefore we consider a gaussian spatial distribution along the field lines, with $\sigma = 5 \times 10^8$ cm. The assumption of symmetrical heating appears to be more justified in this case.

3.2 Simulations

The light curves for the November 12 flare have been fitted using the same procedure as for the May 7 flare. The heating source has the functional form given by equation [1] with:

$$H_o = 10 \text{ ergs sec}^{-1} \text{ cm}^{-3}$$
$$s_o = 2 \times 10^9 \text{ cm.}$$
$$\sigma = 5 \times 10^8 \text{ cm}$$

$$f(t) = \begin{cases} 1 & 0 < t < 180 \text{ seconds} \\ \exp[\,(180 - t)/\tau\,] & t > 180 \text{ seconds} \end{cases}$$

Several cases have been computed for different values of the heating decay time (τ= 0, 30, 60, 140 secs). The model with τ= 60 secs is the one which fits the observations best. Notice that the fitting of FeXXV and CaXIX lines is a very sensitive function of τ, owing to the strong dependence on temperature of the emissivity of these lines.

Fig. 6 shows a comparison of observations and numerical simulation for lines observed with the FCS. The observed light curves are obtained summing the contributions from the three brightest pixels, where a loop-like structure was imaged. The observed fluxes in the OVIII line have been multiplied by a factor of two to take into account an apparent inflight decrease in sensitivity in this channel (Acton 1982, private communication).

As shown in figure 5, fluxes for all the lines, other than NeIX, predicted by our model are in quite satisfactory agreement with observations. Not only is the general time evolution well-reproduced for all lines other than NeIX, but the absolute flux

values also agree with the observations within the estimated accuracy of the FCS calibration. The latter is not known, at present, to better than a factor of two (cf., Pallavicini et al. 1983). Notice that the integrated line fluxes have been obtained from our one-dimensional model by multiplying the observed loop cross section by the computed loop emission per unit area. No free parameter has been arbitrarely introduced to match model predictions with the observations other than the shape, the central position and the normalization of the impulsive heating function. However the high thermal conductivity in the corona makes the detailed shape of the heating function the least important factor among the three.

The discrepancy between the observed and the predicted fluxes for NeIX is at present unexplained. We notice, however, that the ratio of OVIII and NeIX fluxes is not consistent with what would be expected from the emissivity functions calculated by Mewe et al. (1979) and from the assumed chemical abundances (relative to hydrogen) of 2.8×10^{-4} and 4.5×10^{-5}, respectively: the flux ratios should be larger than 10 for all the temperatures greater than $T \sim 10^6$ K. Several explanations are possible, among which a contaminations of the NeIX channel by the nearby iron lines is perhaps most likeky. The occurrence of this contamination could be investigated in the course of the second SMM mission by means of spectral scans around the line center. In the absence of any better resolution of this discrepancy, one could remove the difficulty by arbitrarily decreasing the observed NeIX flux by a factor of two; the data presented above, however, have not been corrected in this *ad hoc* way.

Figure 7 shows the close agreement between the model predictions and the BCS observations of FeXXV and CaXIX resonance line intensities. Notice that the BCS observations have been empirically scaled down by a factor 1.5 to bring them into agreement with the FCS observations. The BCS, in fact, integrates over a much wider field of view than the FCS pixels where most of the FeXXV and CaXIX is detected. The total amount of energy derived from our simulation with $\tau = 60$ secs is $W = 7.2 \times 10^{29}$ ergs. This value, as well as the somewhat smaller value derived for the May 7 flare, falls well within the range of observed energies in compact flares (Svestka 1981, Simnett 1983). The thermal energy is the dominant component of energy, by more than one order of magnitude, at any time in the course of the flare. In figure 8 we present evolution of the total thermal energy in our model.

4. Discussion and Conclusions

The above results show that our numerical simulations can satisfactorly reproduce light curves of coronal lines observed in real flares. For the November 12 flare the agreement can be considered good, especially if one takes into account the uncertainties due to the chemical abundances, FCS absolute calibrations and indeterminacy in the loop cross section. For the May 7 flare, we have been able, so far, to fit only the rise phase both of BCS light curves predicting the termal energy content and to study the start of the decay phase. Even so, however, the comparison has allowed us to put constraints on the energy deposition process and to find agreement with some observations. In particular, we have found that in order to fit the flare with our model, additional energy must be provided during the decay phase even in this compact event.

Keeping in mind that we use only the FeXXV line intensity light curve as a guide to derive the heating evolution and that the modelling depends only on two parameters, the transient heating power and its duration, it is interesting to note that a good fitting of this line leads directly to a good fitting of all the other FCS

and BCS lines. Since the link among the light curves in our computation is provided by the fact that they are computed from a hydrodynamic model our result show that the gradual phase of compact flares is an essentially hydrodynamical phenomenon and that the FeXXV emission is actually a tracer of the impulsive heating characteristics. While it is obvious that this one-dimensional, one-fluid hydro code cannot fully reproduce the complexity of the flare phenomenon in all its details, these simulations do show that it does provide an overall description which has the right macroscopic physics in it and is consistent with the observations of the XRP light curves.

Different considerations apply when we try to consider the influence of small scale effects such as, for instance, turbulent inhibition of thermal conduction, non-linear (but classical) modifications to the Spitzer conductivity, inhomogeneities across the field lines and the like. A description of the physics underlying these phenomena, which would allow us to include these effects in our model, is presently lacking; in fact, many of these basic physical effects are still poorly understood for laboratory plasmas. Prospects of a full understanding of these aspects for astrophysical phenomena thus appear at the moment even more remote.

With these caveats in mind, we can conclude that the numerical simulations provided by our code, as well as by other analogous codes, represent a first encouraging step in comprehensive flare modelling, and are capable of tackling more detailed problems, such as the fitting of line profiles. At the same time, the observations from the second SMM mission should be aimed at providing better diagnostics for placing more stringent constraints on the basic physical assumptions of these models. In particular, high time resolution observations of line intensities and line shapes during the first few seconds of a flare should help in identifying the site of energy deposition, and should allow a more detailed understanding of the dynamic evolution of flare plasmas.

Acknowledgements

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References

Acton, L., W. et al. (1980), *Solar Physics*, **65**, 53

Acton, L., W., Canfield, R., C., Gunkler, T., A., Hudson, H., S., Kiplinger, A., L. and Leibacher, J., W. (1982) *Ap.J.*, **263**, 409

Mac Neice, P. et al. 1984 in preparation

Mewe, R., Schrijver, J., and Sylvester, J.(1980) - *A. and A. Suppl.*, **40**, 323

Pallavicini, R., Peres, G., Serio, S., Vaiana, G., Acton, L., Leibacher, J. and Rosner, R. (1983), *Ap J.*, **270**, 270

Peres, G., Rosner, R., Serio, S. and Vaiana, G., S. (1982), *Ap J.*, **252**, 791

Peres, G., Rosner, R., Serio, S. and Vaiana, G., S. (1983) in *Proc. of the XVI Int. Conf. on Phenomena in Ionized Gases*, Duesseldorf, Aug 29 - Sept 2 1983

Rosner, R., Tucker, W., H., Vaiana, G., S. (1978) *Ap. J.*, **240**, 643

Simnett, G., M.(1983), *Solar Physics*, **88**, 289

Svestka, Z. (1981), in *Solar Flare Magnetohydrodynamics*, edited by E. Priest, Gordon and Breach 1981

Figure captions

Figure 1 - FCS observations of the May 7 1980 flare, time= 0 corresponds to 14:52:00 U.T.

Figure 2 - May 7 1980 flare: synthesized light curves (solid lines) from the model with an instantaneous switch off of the transient heating at time= 150 seconds, and BCS observations (crosses) of Fe XXV and Ca XIX lines. Time = 0 corresponds to 14:54:36 U.T.

Figure 3 - Comparison of synthesized (solid lines) and observed (crosses) photon fluxes for the OVIII and NeIX lines for the decay of the May 7 flare. The model as well the time definition are as in figure 2.

Figure 4 - May 7 1980 flare: synthesized light curves (solid lines) from our model, in the case of an exponential decay of the heating after time= 150 secs with e-folding time= 30 seconds, and BCS observations (crosses) for Fe XXV and Ca XIX lines. The time definition is the same as in figure 2.

Figure 5 - Predicted evolution of the total thermal energy for the same model of the May 7 flare reported in figure 4.

Figure 6 - Predicted (solid lines) and observed (crosses) fluxes for the six lines observed with the FCS for the Nov 12 1980 flare. The model presented here corresponds to a continuous heating up to time= 180 seconds followed by an heating decaying with an e-folding time of 60 seconds. Time = 0 corresponds to 17:00:00 U.T.

Figure 7 - Predicted (solid lines) and observed (crosses) fluxes for the Ca XIX and Fe XXV lines observed with the BCS for the Nov 12 1980 flare. The model as well as the definition of time are the same as in figure 6.

Figure 8 - Predicted evolution of the thermal energy for our model of the Nov 12 1980 flare. The model is the same as in figure 6 and 7.

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Fig 1

May 7 '80 Flare, FCS Obs.
t= 0 is 14:52 U.T.

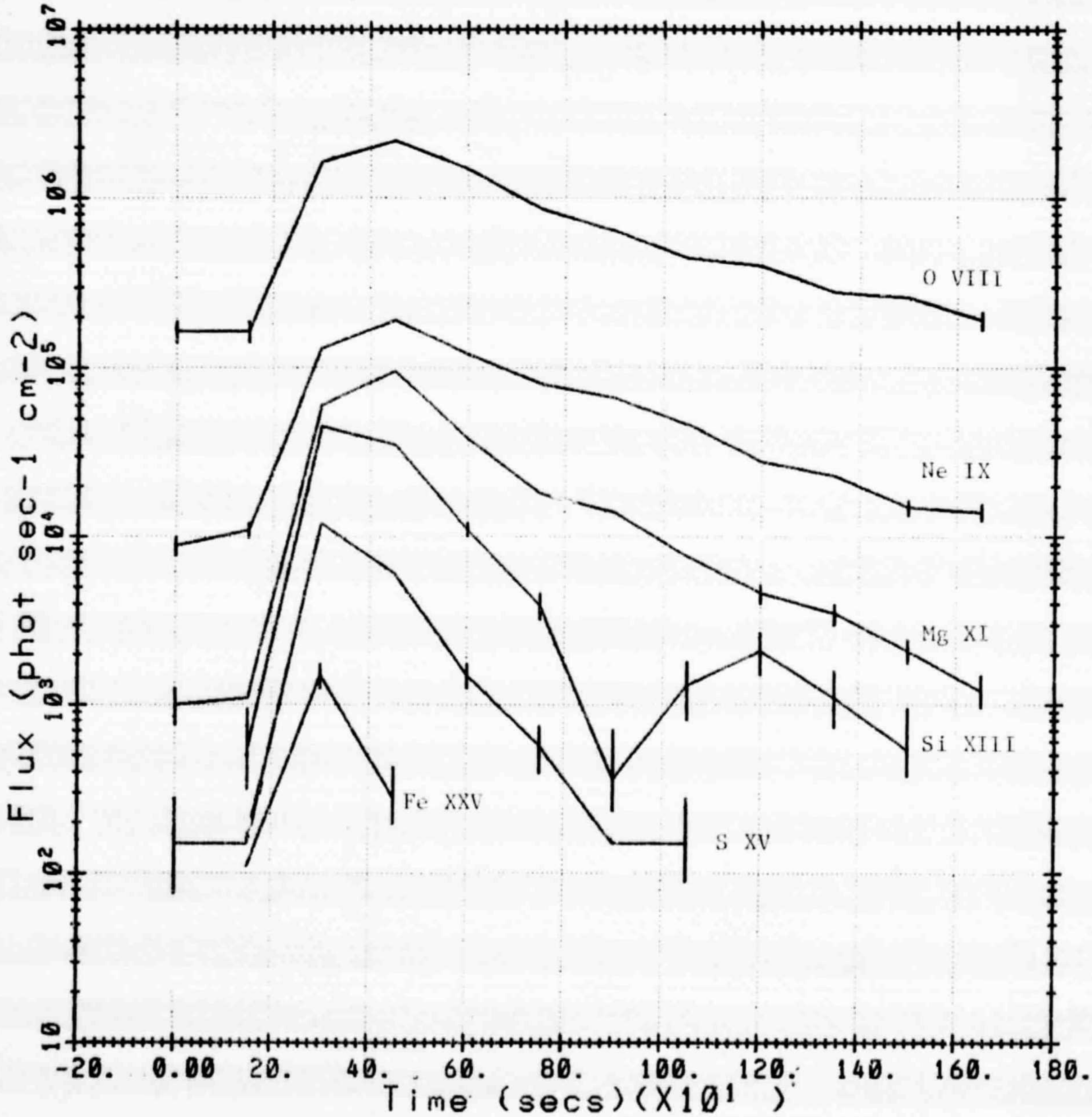

Figure 2

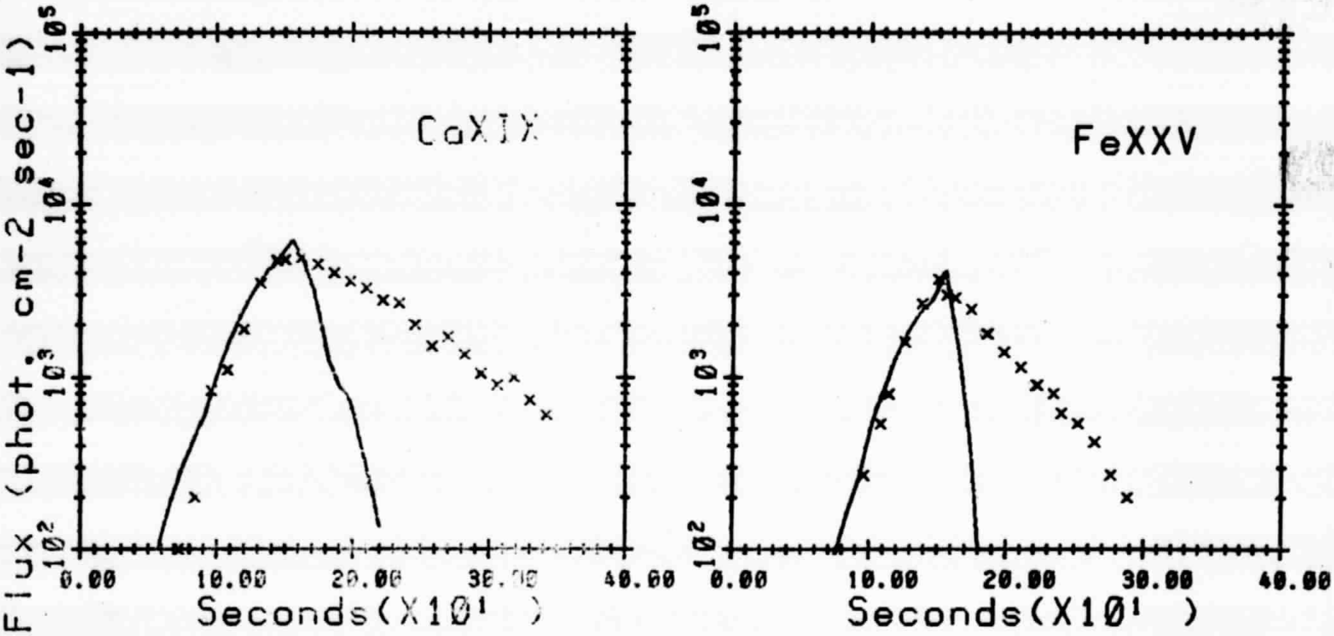
Flux (phot. cm-2 sec-1)
CaXIX
FeXXV
10^5
10^4
10^3
10^2
0.00
10.00
20.00
30.00
40.00
Seconds(X10¹)

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Figure 3

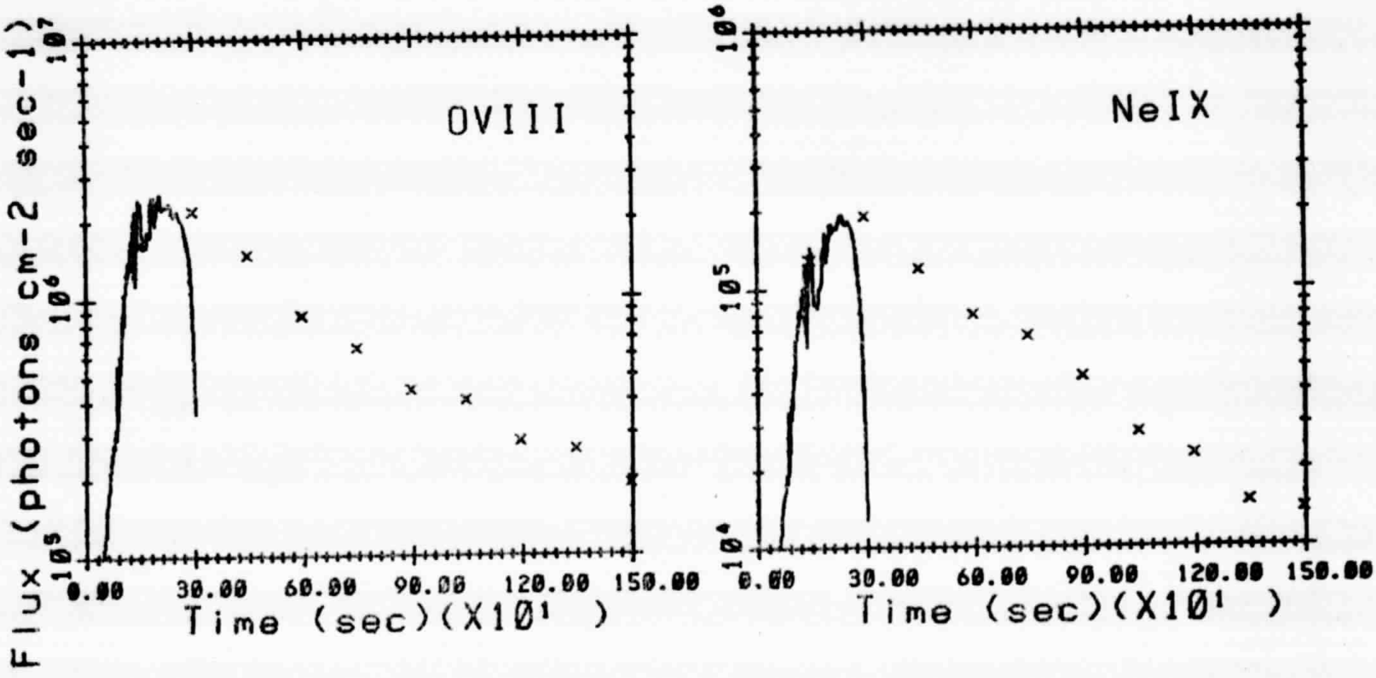

Figure 4

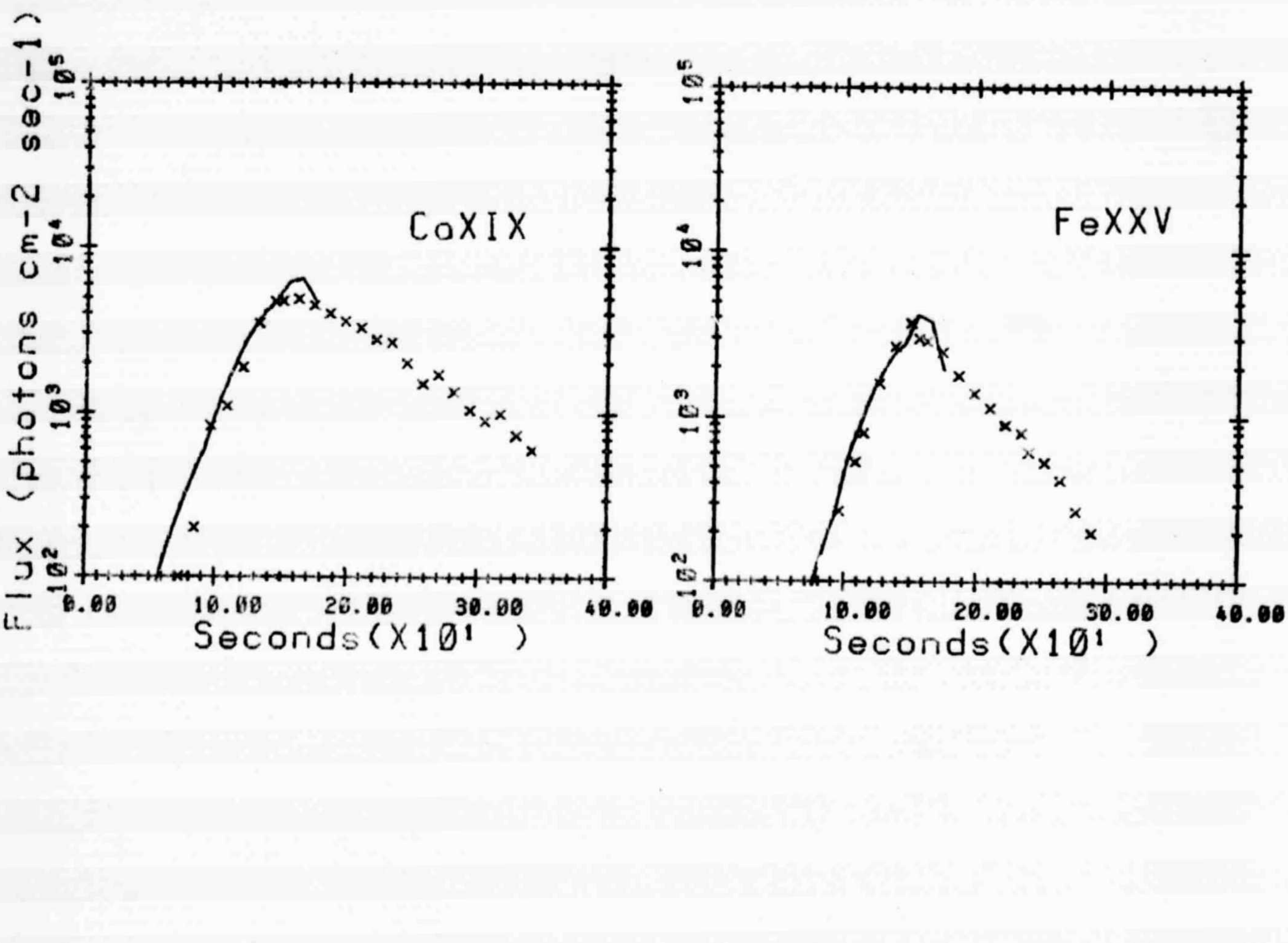
Flux (photons cm-2 sec-1)
CoXIX
FeXXV
Seconds(X10¹)
Seconds(X10¹)
0.00
10.00
20.00
30.00
40.00

Fig 5

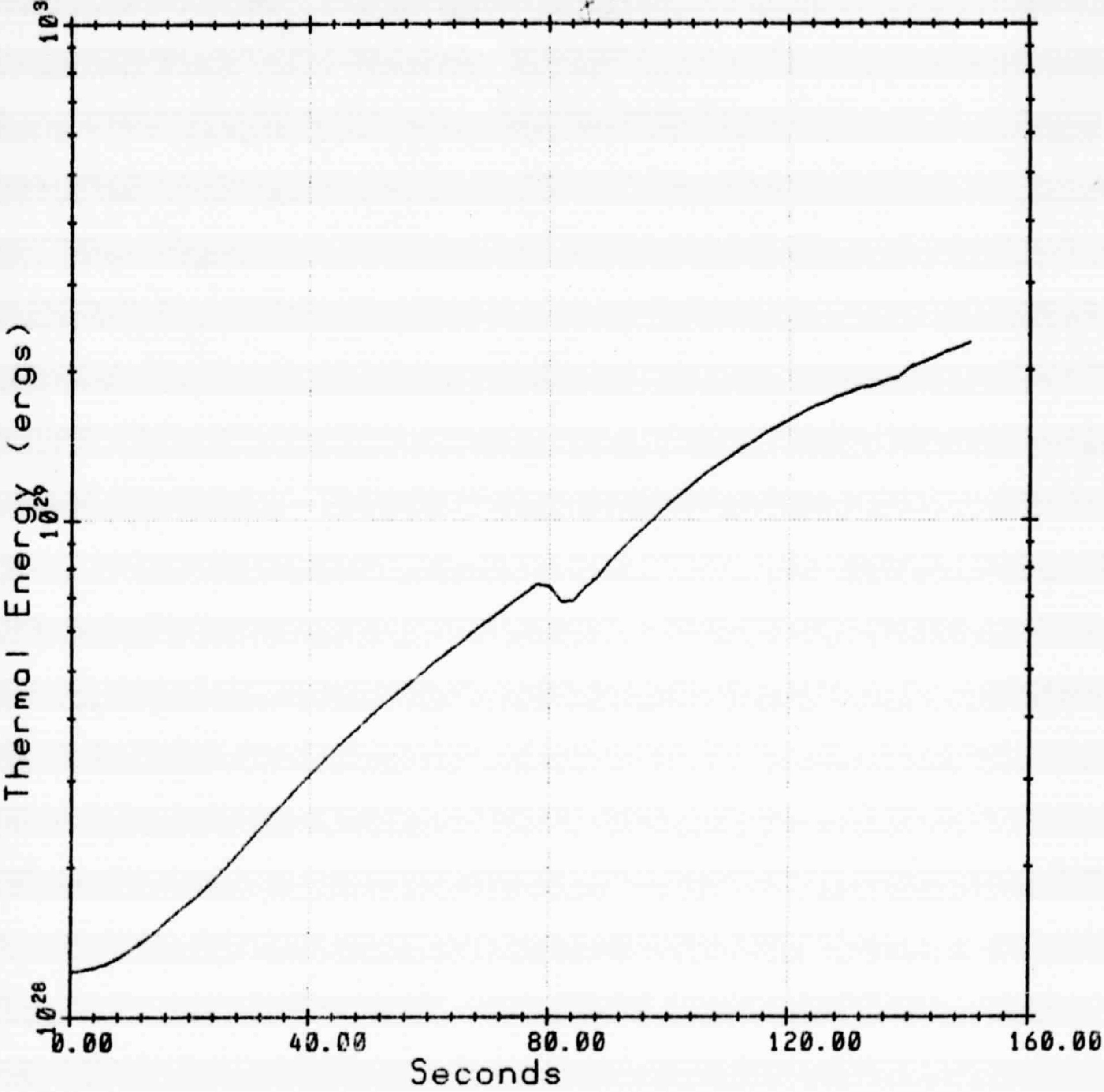
10^{30}
10^{29}
10^{28}
Thermal Energy (ergs)
0.00
40.00
80.00
120.00
160.00
Seconds

Figure 6

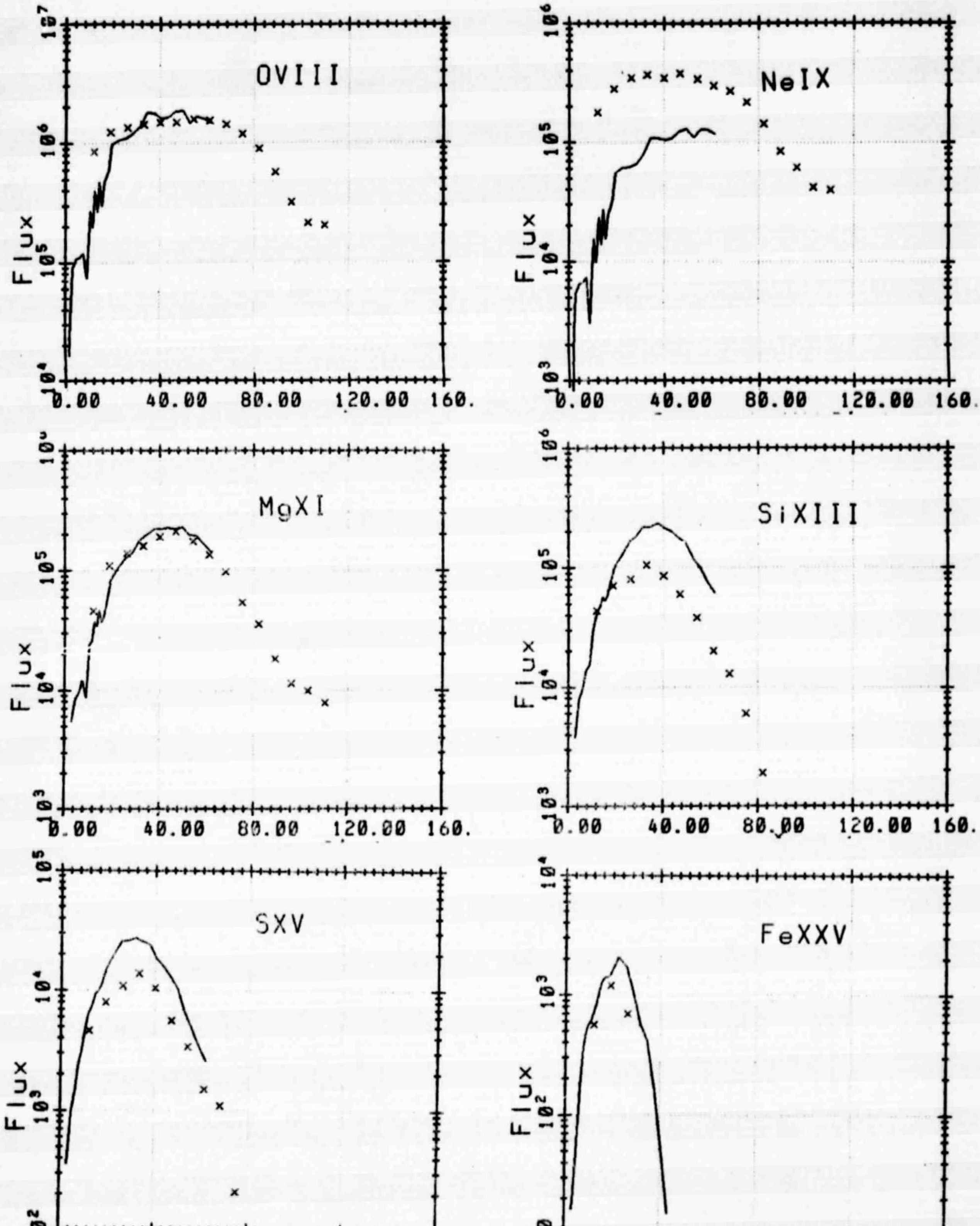

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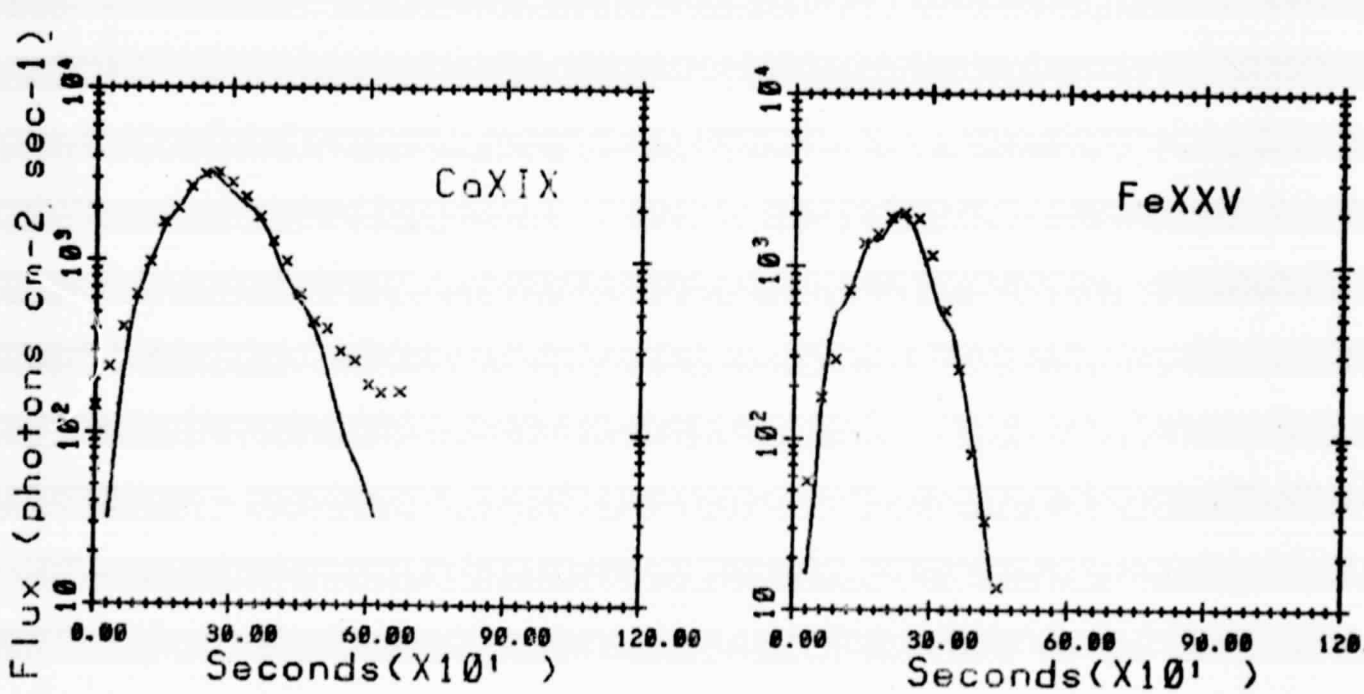
Figure 7


Flux (photons cm-2 sec-1)
CaXIX
FeXXV
10^4
10^3
10^2
10
0.00
30.00
60.00
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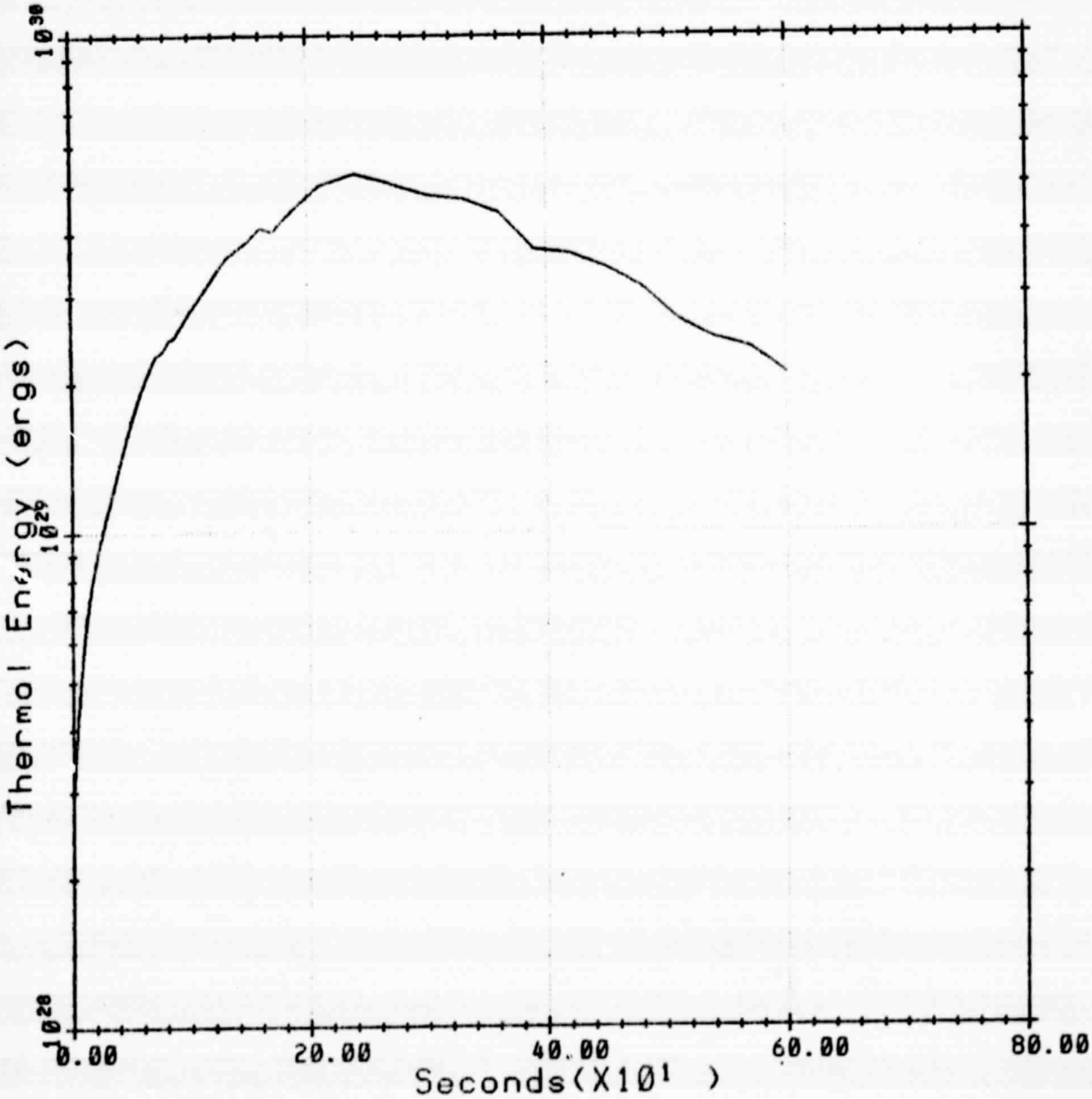
120.00
Seconds(X10¹)
Seconds(X10¹)
120.

Fig 8



10^{30}
10^{29}
10^{28}
Thermal Energy (ergs)
0.00
20.00
40.00
60.00
80.00
Seconds(X10^1)